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A Comparison of the Normal Tolerance Limit and Bootstrap Methods With Application to Spacecraft Acoustic Environments

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by

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ABSTRACT

Vibroacoustic test levels are required in order to properly accept and qualify spaceflight hardware that is exposed to high levels of acoustic excitation during launch. Traditionally, NASA has utilized the one-sided Normal Tolerance Limit method in deriving these levels from applicable acoustic flight data. This paper compares the results obtained from the Normal Tolerance Limit method with those obtained from the Bootstrap method. The Bootstrap is a statistical subsampling method which utilizes sample data to generate replicates which are utilized for parameter and confidence interval estimation. The Bootstrap makes no assumption on the underlying distribution of the data, whereas the Normal Tolerance Limit assumes normality. These two methods will be used on a sample collection of Titan IV internal payload fairing sound pressure level data which are representative of the liftoff acoustic environment seen by the Cassini spacecraft. Results of each method are presented and compared.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFSSD	Air Force Space Systems Division
BS	Bootstrap
CDF	cumulative distribution function
dB	decibel(s)
EEE	extreme expected environment
ETR	Eastern Test Range
g	acceleration due to gravity (9.81 m/s^2)
Hz	Hertz
LC	launch complex
MEE	maximum expected environment
MEFL	maximum expected flight level
MPE	maximum predicted environment
NASA	National Aeronautics and Space Administration
NTL	normal tolerance limit
OTOB	one-third octave band
Pa	Pascals
PLF	payload fairing
rms	root-mean-square
SPL	sound pressure level
μPa	micro-Pascals

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Chapter 1

Introduction

1.1 Background

Numerous types of spaceflight hardware (spacecraft, space experiments, launch vehicle components) are exposed to time-varying random excitation during the three distinct launch events of liftoff, transonic flight and maximum flight dynamic pressure. For a large launch vehicle these random acoustic levels can exceed 160 decibels or dB (reference to 20 μPascals) in overall sound pressure level. Acoustic loads occurring at the liftoff event are generated by the turbulent mixing of the rocket engines' exhaust gases with the atmosphere. Aerodynamic pressure fluctuations (aerodynamic noise) occur during the transonic flight regime at vehicle Mach numbers from 0.7 to 1.3 and are due to separated flow from shock wave-boundary layer interactions. Additional fluctuating pressure waves are generated in the turbulent aerodynamic boundary layer between the vehicle's exterior surface and the atmosphere during flight, and peak when the flight dynamic pressure on the vehicle is at its maximum (known as max q). The nonstationary vibroacoustic measurements obtained from a launch are usually analyzed separately for each of the three launch events. Acoustic data measured during a liftoff will be used later as the data source for this paper's main analytical topic.

Part of the acoustic energy seen at launch, external to the vehicle, is transmitted through the vehicle's outer protection layer (payload fairing (PLF) for an expendable launch vehicle or Shuttle cargo bay wall for the Space Shuttle). The resulting internal acoustics excite the spaceflight hardware, resulting in this hardware being exposed to high levels of random vibration. Hardware with large area and low mass, such as antenna dishes, solar panels or thermal radiators, are particularly susceptible to this acoustic excitation. Other delicate optical or electronic components, such as cameras, avionics boxes and communication systems, may also be damaged by this acoustic excitation.

In order to ensure mission success, it is necessary for NASA (National Aeronautics and Space Administration) to determine this internal acoustic environment for the launch vehicles that it utilizes. Knowledge of these environments allows spaceflight hardware to be properly designed for the structural loading that it will experience during launch. Normally the spaceflight hardware will undergo dynamic testing on the ground to specified test levels. Typically acceptance testing of flight hardware is performed at levels representing the maximum expected flight environment; whereas qualification testing of the hardware design is performed at levels which exceed the maximum expected flight environment with some margin added to increase the hardware's likelihood of flight success.

1.2 Nonstationary Random Vibroacoustic Data Analysis

Both external (to the launch vehicle) and internal (inside an expendable launch vehicle's PLF or inside the Shuttle's cargo bay) measurements of the acoustic pressures may be obtained during launch. The pressure time histories, x (t), obtained are time-varying data from a nonstationary random process (Figure 1-1). Because this measured signal comes from a random (non-deterministic) source it can not be described by a deterministic, periodic mathematical expression since it will not exactly repeat after some finite period of time. If the source was stationary random, it could be described by the statistical values of its ensemble properties, such as its mean (μ_x), standard deviation (σ_x), and rms (root-mean-square) value (Ψ_x), which would be invariant over time. However, for nonstationary random sources these statistical values are time varying. It is often convenient to compute these time-varying average values over short, contiguous segments of the measurement signal to obtain running averages of these values.

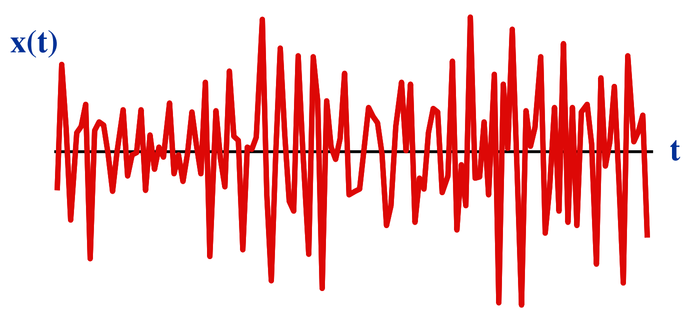

Figure 1-1: **Nonstationary random data, x(t)**

For example, the one-third octave band (OTOB) spectra sound pressure level (SPL) for a stationary pressure time history, x(t) (where x represents pressure and t represents time), is given in dB by:

$$L_x(f_i) = 10\log_{10}\left(\frac{\Psi_x(f_i)}{\Psi_{ref}}\right)^2 \qquad \mathbf{1.1}$$

where $\Psi_x(f_i)$ is the rms value of the pressure signal x(t) filtered through a one-third octave bandpass filter centered on frequency f_i, and Ψ_{ref} is a reference rms pressure commonly set to be 20 μPa for acoustic data.

For a nonstationary pressure time history a time-varying SPL spectrum may be estimated from a running average of the time-varying rms value. This is obtained by replacing $\Psi_x(f_i)$ in Eq. **1.1** by

$$\hat{\Psi}_x(f_i,t) = \left[\frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} x^2(f_i,t)dt\right]^{\frac{1}{2}} \qquad \mathbf{1.2}$$

where the hat (^) represents an estimate, $x^2(f_i,t)$ is the instantaneous squared value of the pressure signal passed through the ith one-third octave bandpass filter, and T is the averaging time of analysis. For launch vehicle vibroacoustic data, a T=1.0 second with

50 percent overlapping has been found to be a reasonable value to use which balances the random error and the bias error inherent to this process (Reference [1]).

A single spectrum, referred to as the “maximax” spectrum, is then obtained by selecting at each OTOB frequency the largest value from all the time-varying SPL spectra, regardless of which time slice it originates. This maximax SPL spectrum does not represent the instantaneous SPL at any specific time but instead it has been found to provide a conservative measure of the dynamic environment with respect to the damage potential of this signal to spaceflight structures and equipment. A degree of conservatism (perhaps substantial) is incorporated into the analysis with the usage of maximax spectrum.

References [1] and [2] are two excellent sources of information regarding the acquisition and analysis of dynamic data.

1.3 Setting Vibroacoustic Test Specifications

To properly test qualify spaceflight hardware to its launch acoustic environment, test levels are set based upon the appropriate maximax SPL spectra available. Typically regions called zones are defined in a launch vehicle where it is expected that the acoustic environment within that zone will be reasonably similar. For example, a section within the cylindrical PLF where a spacecraft is relatively uniform in geometry could be one zone. Another zone could be all PLF frames of a particular size and construction even though they may be spatially spread throughout the fairing.

It is also known that for a given launch vehicle there will be flight-to-flight variations. Some of this variability may be due to inherent differences between the flights such as different launch complexes, payload configuration and weight. But some of this variability is due to the randomness of the launch event itself, such as a hot engine burn or a three-sigma max q event. Due to the limited amount of available flight data, it is typical to include in the database as much flight data as possible to capture this true variability. For example, data from two similar launch complexes at NASA's Kennedy Space Center might be used together in setting a test level, but data from a launch of the same vehicle at the U.S. Air Force's Vandenberg Air Base may be deemed to be of a different family of data.

Given a set of data, levels are typically derived that represent the maximum expected environment (MEE). This level is also known as the maximum predicted environment (MPE) and as the maximum expected flight level (MEFL). This is a level that would typically not be exceeded, and should account for both the expected spatial variation within a particular zone as well as the known flight-to-flight variation.

A second higher level denoted as the Extreme Expected Environment (EEE) is a level that should not be exceeded except for the most extreme circumstances. The EEE level is meant to cover known and unknown failure modes due to peak loading.

This paper will illustrate two different methods used to calculate the MEE and EEE test levels. These two methods are: (1) the one-sided Normal Tolerance Limit method (NTL) and (2) the Bootstrap method. The NTL has traditionally been utilized by both NASA and the U.S. Air Force Space Systems Division (AFSSD) to calculate its MEE and EEE levels that are used for acceptance and qualification testing respectively. The Bootstrap method is a statistical subsampling method that has wide use in many disciplines but is believed by this author to be new for this specific aerospace application. Both methods will be applied to a set of liftoff launch vehicle acoustic data and their respective results will be compared in this paper. The data set utilized for this study characterizes the acoustic environment of a spacecraft at liftoff via a Titan IV launch vehicle. This data was originally analyzed for the Cassini spacecraft, a NASA mission whose purpose is to observe and study Saturn and its moons. For Cassini it was necessary to reduce this liftoff acoustic environment via enhanced PLF blanket treatments.

Chapter 2

NASA's Traditional Method of Setting Vibroacoustic Test Levels

2.1 Normal Tolerance Limit Method

There are a number of different methods that could be applied to a set of measured data to compute vibroacoustic test levels. NASA, and the U.S. AFSSD, has traditionally used what is called the Normal Tolerance Limit (NTL) method to compute vibroacoustics test levels (References [3], [4]).

Normal tolerance limits should be applied only to normally distributed random variables. If this is true, then the one-sided normal tolerance limit (NTL_x) for the set of x variables, x_i; i=1, 2,…, n is given by:

$$NTL_x(n,\beta,\gamma) = \overline{X} + (K_{n,\beta,\gamma} \times s_x) \qquad \textbf{2.1}$$

where

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i = \text{sample mean of x} \qquad \textbf{2.2}$$

$$s_x = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(x_i - \overline{X})^2} = \text{sample standard deviation of x} \qquad \textbf{2.3}$$

$K_{n,\beta,\gamma}$ = one-sided normal tolerance factor β= minimum portion (probability) of all values that will be less than

$NTL_x(n, \beta, \gamma)$

γ= confidence coefficient associated with $NTL_x(n, \beta, \gamma)$

The one-sided normal tolerance K factors may be easily found in Reference [5]. A subset of these K factors is provided in Table 2-1. The magnitude of the K factor is affected by both the probability desired and the confidence desired. This uncertainty in the confidence results from using a sample mean and sample standard deviation in lieu of the true (entire) population's mean and standard deviation values.

Note, for the case of $n = \infty$ the confidence is one-hundred percent, since one has the entire data population and not just a sample subset to utilize. One can therefore calculate with 100 percent confidence the population's true mean and true standard deviation. For this special case, the K one-sided normal tolerance factors become the z_α percentage point of the standardized normal distribution. Then

$$NTL_x(\infty, \beta) = \mu_x + (z_\alpha \times \sigma_x), where\, \alpha = 1 - \beta \qquad \textbf{2.4}$$

Where μ_x is the true mean, and σ_x is the true standard deviation of x. The z_α values for the standard normal random variables may be found in numerous texts, including Reference [6].

Table 2-1: **One-Sided Normal Tolerance K Factors (from Reference [2])**

n	γ=0.50			γ=0.75			γ=0.90		
	β=0.90	β=0.95	β=0.99	β=0.90	β=0.95	β=0.99	β=0.90	β=0.95	β=0.99
3	1.50	1.94	2.76	2.50	3.15	4.40	4.26	5.31	7.34
4	1.42	1.83	2.60	2.13	2.68	3.73	3.19	3.96	5.44
5	1.38	1.78	2.53	1.96	2.46	3.42	2.74	3.40	4.67
6	1.36	1.75	2.48	1.86	2.34	3.24	2.49	3.09	4.24
7	1.35	1.73	2.46	1.79	2.25	3.13	2.33	2.89	3.97
8	1.34	1.72	2.44	1.74	2.19	3.04	2.22	2.76	3.78
9	1.33	1.71	2.42	1.70	2.14	2.98	2.13	2.65	3.64
10	1.32	1.70	2.41	1.67	2.10	2.93	2.06	2.57	3.53
12	1.32	1.69	2.40	1.62	2.05	2.85	1.97	2.45	3.37
14	1.31	1.68	2.39	1.59	2.01	2.80	1.90	2.36	3.26
16	1.31	1.68	2.38	1.57	1.98	2.76	1.84	2.30	3.17
17	1.31	1.68	2.37	1.55	1.96	2.74	1.82	2.27	3.14
18	1.30	1.67	2.37	1.54	1.95	2.72	1.80	2.25	3.11
20	1.30	1.67	2.37	1.53	1.93	2.70	1.76	2.21	3.05
25	1.30	1.67	2.36	1.50	1.90	2.65	1.70	2.13	2.95
30	1.29	1.66	2.35	1.48	1.87	2.61	1.66	2.08	2.88
35	1.29	1.66	2.35	1.46	1.85	2.59	1.62	2.04	2.83
40	1.29	1.66	2.35	1.44	1.83	2.57	1.60	2.01	2.79
50	1.29	1.65	2.34	1.43	1.81	2.54	1.56	1.96	2.74
∞	1.28	1.64	2.33	1.28	1.64	2.33	1.28	1.64	2.33

2.2 Example of Normal Tolerance Limit Method

As a simple illustration of the NTL application, let x be a sample set of 5 data points which are believed to come from a normal distribution. Let the sample mean, $\overline{X}$ = 120, and let the sample standard deviation, s_x= 5. Then the NTL for this example is given by Equation **2.1** as

$$NTL_x(n,\beta,\gamma) = \overline{X} + (K_{n,\beta,\gamma} \times s_x) = 120 + (K_{n,\beta,\gamma} \times 5) \qquad \mathbf{2.5}$$

If one wanted the 95 percent probability level with 50 percent confidence, then K=1.78 (for n=5) and

$$NTL_x(5,0.95,0.50) = 120 + (1.78 \times 5) = 128.9 \qquad \textbf{2.6}$$

The interpretation of this result is that one has 50 percent confidence that at least 95 percent of all future data taken from this population source will be less than the level of 128.9.

Suppose one wanted to increase this confidence to 90 percent for this example. This would result in increasing the K factor from 1.78 to 3.40, leading to

$$NTL_x(5,0.95,0.90) = 120 + (3.40 \times 5) = 137.0 \qquad \textbf{2.7}$$

One notes, as seen in Table **2-1**, that there is a heavy price to be paid for increasing the level of confidence, particularly when n, the number of data points, is small. Such higher (test) levels may drive the structural hardware design to be made stronger (i.e. added weight, different materials) or alternatively, costly mitigation treatments, in terms of money and launch weight (i.e. isolation systems, acoustic blankets), may be required to lower the dynamic environment to desired levels.

Additional information on the usage of the NTL for aerospace applications is found in References [**2**], [**3**], [**7**], [**8**], and [**9**].

2.3 Lognormal Distributions and the NTL

As stated in Section 2.1 the Normal Tolerance Limit method should be applied to normally distributed random variables. There is much evidence that many data sets applicable to spaceflight vibroacoustic data are not normal but indeed lognormal (References [10], [11], [12], [13], [14], [15], and [16]).

Therefore, one may still use the NTL method on this data by making use of a logarithmic transformation, as follows

$$y = \log_{10} x \qquad \textbf{2.8}$$

$$NTL_y(n, \beta, \gamma) = \bar{y} + (K_{n,\beta,\gamma} \times s_y) \qquad \textbf{2.9}$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \quad = \text{sample mean of y} \qquad \textbf{2.10}$$

$$s_y = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad = \text{sample standard deviation of y} \qquad \textbf{2.11}$$

The normal tolerance limits in the original units of x may then be recovered by

$$NTL_x(n, \beta, \gamma) = 10^{NTL_y(n,\beta,\gamma)} \qquad \textbf{2.12}$$

This would be the likely procedure to use if the data was a vibration response in g^2/Hz or a shock response spectrum in g's since this type of data are generally believed to be lognormally distributed.

For the case of acoustic SPL data in dB, one can generally use these data in the NTL method directly, without any need for transformation. This is because the pressure data are assumed to be lognormal, which would make the SPL dB data normally distributed due to its calculation via

$$SPL(dB) = 10\log_{10}\left(\frac{p}{p_{ref}}\right)^2 = 20\log_{10}\left(\frac{p}{p_{ref}}\right) \qquad \textbf{2.13}$$

2.4 Commonly Used NTL Levels

Both NASA and the U.S. AFSSD have standardized their MEE (or MPE or MEFL) to be the NTL (β=0.95, γ=0.50) level. This is commonly referred to as the P95/C50 or P95/50 level. Most other application areas, such as in civil engineering, would require a much higher confidence coefficient. For example, fatigue life (S-N) curves for materials are based on a P95/C95 level (Reference [17]), as is soil contamination analyses for oilfield brine (Reference [18]) and groundwater (Reference [19]) cleanup. Still the P95/C50 level, in conjunction with using maximax spectra data, has proven successful in establishing maximum expected flight levels for use in the test verification of spacecraft and payload flight hardware.

The original use of the fifty percent confidence coefficient arose from the predicament in which the AFSSD historically had only one measurement available to use to set an environment. Because that one measurement had an even chance of either being greater or less than the actual mean, it in effect provided a fifty percent level of confidence. For consistency this P95/C50 level was maintained even when sufficient measurements later became available to allow for higher confidence levels to be calculated. It was argued then that the added test margin would cover the lack of conservatism in the fifty percent confidence level. Later, NASA, again for consistency, adopted the same P95/C50 level as their MEE level.

Although using a confidence level of only fifty percent, in setting spacecraft hardware acceptance test levels, may seem to be un-conservative this philosophy has served the aerospace industry very well for over 40 years. When taken as a whole, there are many conservative aspects of the entire test and data analysis process that may tip the balance toward conservatism. Some of these aspects include using a maximax derived test level, hardmounting of components during random vibration shaker testing, liberal envelopment of spectral peaks and valleys when setting test levels from random data, and built-in testing margin on both level and time duration.

For many years, the qualification test levels were set to MEE plus some qualification margin, where this margin varied among organizations. For example, the AFSSD used a +6 dB margin, whereas many NASA centers used a +3 dB margin.

A few years ago, the Aerospace Corporation, contractor for the AFSSD, concluded that an extreme expected environment (EEE) of P99/C90 or a NTL (β=0.99, γ=0.90) level was the appropriate level to represent the qualification test levels (Reference [**20**]). This statistically based qualification level replaced past use of a fixed (+6 dB) qualification margin and takes advantage of using the flight data that are available. This level was also deemed to be consistent with their past experience (accounting for a typical spatial standard deviation of 6 dB within a zone, and a typical 3 dB flight-to-flight variation). Furthermore this P99/C90 level would still maintain their +6 dB qualification margin if only one data sample was available.

Since the Titan IV launch vehicle program is managed by the AFSSD, this P99/C90 EEE level pertains to all missions that launch on the Titan IV vehicle. Thus even though the Cassini spacecraft was a NASA mission, the P99/C90 EEE philosophy (and not NASA's MEE +3 dB normal philosophy) is pertinent to this spacecraft since it was launched on a Titan IV vehicle.

In summary, the vibroacoustic test levels for the Cassini spacecraft were based on using the following one-sided NTL philosophy:

<ins>Maximum Expected Environment</ins> (MEE used as basis for acceptance level testing):

NTL (β=0.95, γ=0.50) level = P95/C50

<ins>Extreme Expected Environment</ins> (EEE used for qualification level testing):

NTL (β=0.99, γ=0.90) level = P99/C90

Chapter 3

The Bootstrap Method

3.1 Background

The advances made in computational speed and cost in the 1970's allowed for numerous advances in statistical theories and methods. The Bootstrap is one of these methods. The Bootstrap was developed by Efron of Stanford University and introduced in his 1977 Rietz Lecture "Bootstrap Methods: Another Look at the Jackknife" (Reference [21]). In this paper, Efron discusses the problem "given a random sample X = (X_1, X_2,….X_n) from an unknown probability distribution F, estimate the sampling distribution of some prespecified random variable R(X,F), on the basis of the observed data x."

The Bootstrap thus permits assessment of the accuracy and uncertainty of estimated parameters from small samples, without any prior assumptions about the underlying distribution. It is no longer necessary to assume that the data are normally distributed (as in the NTL method). The Bootstrap also has the advantage of allowing statistical analysis of parameters for which no closed form, even approximate, analysis is available, for example, statistically analyzing the median of a set of data.

The method consists of repeatedly forming bootstrap replicate samples (perhaps as few as 100 for parameter estimation up to a few thousand for confidence interval estimation) of the same size (n) as the original data sample. Each value in the original data sample is assigned an equal probability of $1/n$. The elements of these bootstrap samples are randomly chosen from the original data, with replacement. Thus, a particular sample data point may be chosen several times or perhaps not at all in any particular bootstrap sample. The parameter of interest is then evaluated for each of the bootstrap samples generated. Each computation produces a bootstrap replicate of the parameter of interest. The numerous bootstrap replicates of this parameter provide the information required to estimate a probability distribution for this parameter. This is the sampling distribution of the parameter estimator. From this distribution, confidence intervals, standard error, bias, etc., may be established.

The Bootstrap gets its name from the phrase "to pull oneself up by one's bootstrap." Efron (Reference [**22**]) attributes this to one of the "Adventures of Baron Munchausen" written by Rudolph Erich Raspe. Just as the Baron was able to save himself by "pulling himself up by his own bootstrap" similarly Efron believes that through using the sample data one can statistically pull oneself up to generate new data sets to produce meaningful statistical inferences.

An excellent overview of the Bootstrap method is given in the book "An Introduction to the Bootstrap" (Reference [**22**]). Efron has also written numerous articles on the basic Bootstrap method, as well as on advanced procedures (References [**23**], [**24**], and [25]). In 2003, *Statistical Science* devoted an entire special issue (Reference [26]) of its journal to celebrate the silver anniversary of the Bootstrap. This issue contains 15 papers discussing the impacts, applications and recent developments of this method.

Recently, Paez, of the Sandia National Laboratory, has authored or co-authored numerous articles showing the application of the Bootstrap method to the field of structural dynamics, vibroacoustics and shock (References [27], [28], [29], [30], [31], [32] and [33]).

The Bootstrap has been used to analyze data in virtually all fields including astronomy, biology, phylogeny, econometrics, meteorology, finance and psychology. Relative to the field of acoustics the Bootstrap method has been used for such diverse applications as: (1) assessing the response of gray whales to low-frequency sounds, (2) estimating the uncertainty in fisheries echosounder calibration, (3) evaluating the performance of sensor array processing, and (4) analyzing the role of importance sampling in the establishment of normal ranges for speech characteristics.

3.2 Bootstrap Method

The following steps outline the basic process implementing the Bootstrap method.

(1) Start with a set of data, $X_j = (x_1, x_2, \ldots x_n)$ which forms the sample set taken from the population that has an unknown probability distribution F.

(2) Select a bootstrap sample of these data by randomly sampling, with replacements, the data X_j. The bootstrap replicate, X_b, should be of size n. For example, if n=5, then

$$X_j = (x_1, x_2, x_3, x_4, x_5)$$

and one bootstrap replicate might be

$$X_b = (x_3, x_5, x_3, x_4, x_1)$$

(3) Compute the measure of interest θ; for example if θ = mean (X), then

$$\theta_b = \text{mean}\ (X_b) = \overline{X}_b = \frac{1}{n}\sum_{j=1}^{n} X_{bj} = \frac{(x_3 + x_5 + x_3 + x_4 + x_1)}{5}$$

(4) Repeat steps 2 and 3 numerous times to obtain a large number (B) of bootstrap samples,

$$B = \{X_{b_1}, X_{b_{2,}}, X_{b_3}, \ldots .X_{b_B}\}$$

and bootstrap replicates of the measure of interest

$$\theta_B = \{\theta_{b_1}, \theta_{b_2}, \theta_{b_3}, \ldots .\theta_{b_B}\}$$

(5) Form an empirical cumulative distribution function (CDF) of the measure of interest.

(6) Confidence limits or intervals for the measure of interest may then be based on the CDF. For example, the (1-α) x 100 percent confidence limit is found as the (1-α) × 100 percent percentage point of the empirical CDF.

3.3 Numerical Example

The following numerical example illustrates the Bootstrap procedure of Section 3.2.

(1) Sample data: X_j = (106.2, 111.7, 103.7), where n=3 for this example

And sample mean of data = $\frac{(106.2 + 111.7 + 103.7)}{3}$ = 107.2

(2) Number of bootstrap replicates (B) = nr = 5

Index (j) for the 5 bootstrap Replicate Sets, idx =

$$\begin{matrix} 2 & 3 & 3 & 2 & 1 \\ 3 & 3 & 2 & 1 & 3 \\ 3 & 2 & 1 & 2 & 2 \end{matrix}$$

Columns of indices provide values for random selection of bootstrap replicates, e.g. bootstrap replicate # 1 (column # 1 above) consists of the 2nd, 3rd, and 3rd data points from sample data, or

$$X_{b_1} = (111.7,\ 103.7,\ 103.7)$$

(3) Let the measure of interest be the mean.

Therefore, the Mean of bootstrap replicate # 1 = $\frac{(111.7 + 103.7 + 103.7)}{3} = 106.4$

And the Mean of each of the 5 bootstrap replicates = (106.4,106.4, 107.2, 109.9, 107.2)

And the Mean of the 5 bootstrap replicate means = 107.4

One sees that in this example, the mean of the 5 bootstrap replicate means (107.4) is quite close to the original sample mean (107.2), even for just 5 bootstrap replicates.

Note Steps 4 and 5 of Section **3.2** are not illustrated here due to the simplicity of this particular example.

Chapter 4

The Titan IV Liftoff Acoustic Database

4.1 Background

The goal of this investigation is to perform two statistical analyses on a given set of data. I first use the Normal Tolerance Limits method to calculate the P95/C50 and P99/C90 levels, and next compute "equivalent" results using the Bootstrap Method, and finally compare those results. For this analysis, seventeen acoustic microphone measurements obtained from liftoff events for six different launches of the Titan IV expendable launch vehicle were used.

The acoustic environment of the Titan IV vehicle was studied extensively by NASA in the mid-1990's (References [34], [35]). Conclusions drawn from this study were utilized to analyze the qualification of the Cassini spacecraft (Figure Figure 4-1) to its expected dynamic environment. Early studies showed that it was necessary to reduce the acoustic levels inside the Titan IV payload fairing in order to prevent an extremely costly redesign and requalification of the spacecraft's nuclear power source. An extensive test program was performed that resulted in enhanced PLF acoustic blankets being developed. Full scale PLF ground testing (Figure 4-1) verified that these blankets reduced the acoustics as required for the Cassini mission (References [36], [37], [38], [39], [40], [41]). These enhanced blankets were implemented for the launch of the Cassini spacecraft in 1997 and the flight data indicated that they had indeed successfully performed as desired in reducing the acoustics exciting the Cassini spacecraft (References [42], [43]). In 2004, Cassini reached its goal of Saturn, and it has been performing extremely well to date observing this planet and its various moons.

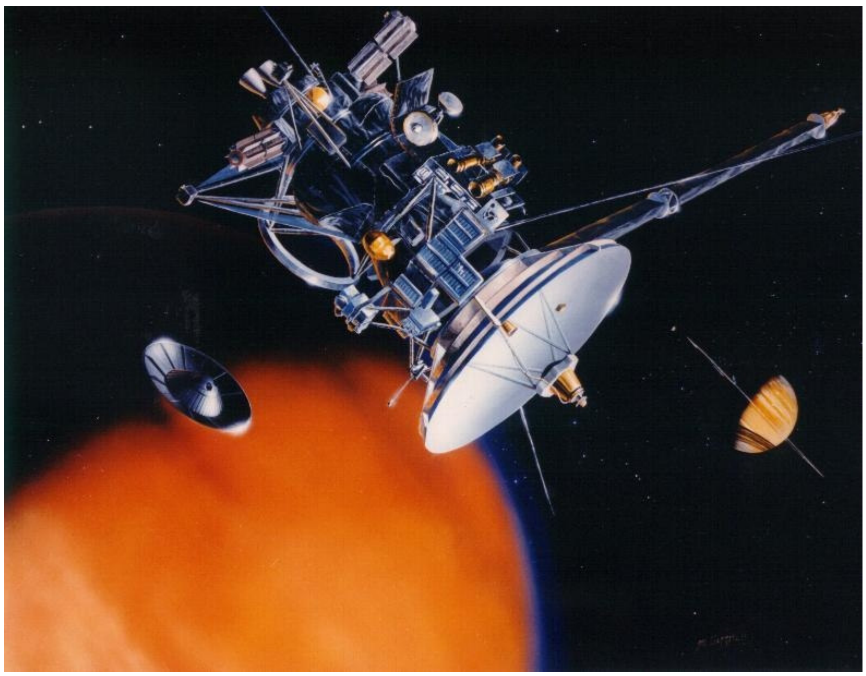

Figure 4-1: **Artist's conception of Cassini releasing the Huygens Probe onto Saturn's moon of Titan. (courtesy of NASA-C-93-05472)**

Figure 4-2: **(left) Titan IV payload fairing in acoustic test chamber; (right) Mockup of Cassini Spacecraft on Centaur upper stage in Lockheed Martin's acoustic test chamber (shown without PLF).**

4.2 Acoustic Database Description

Figure 4-3 illustrates the Cassini spacecraft within the Titan IV launch vehicle's PLF. Understanding the acoustic environment within the PLF in PLF zones 7 through 10 was of critical interest.

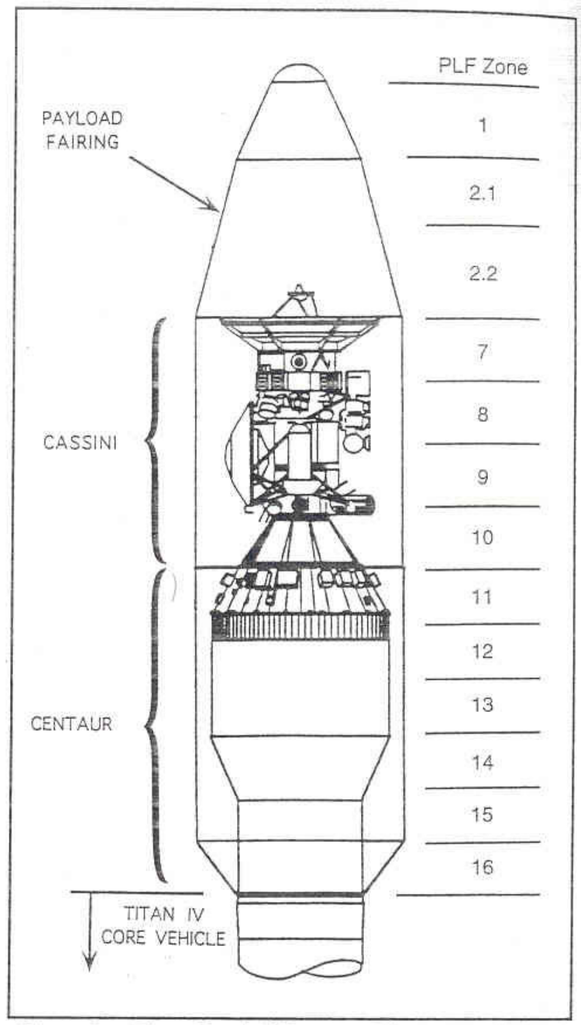

Figure 2: The Cassini/Centaur/Titan IV Launch Configuration

Figure 4-3: **The Cassini spacecraft configured inside the Titan IV payload fairing (from Reference [41]).**

In order to quantify the liftoff acoustic environment for Cassini, previous Titan IV flight data were analyzed. The data utilized corresponded to flight measurements made inside the Titan IV payload fairing at the spacecraft's location. Figure **4-4** shows the locations of the microphones flown on eight different Titan IV flights. For the actual Cassini analysis, flight data from all eight of these flights were used to derive the Cassini acoustic criteria. Both PLF interior microphones as well as microphones mounted on the Centaur forward adapter were used.

For this paper, only the PLF interior microphones were used. The acoustic data from 20 Hz to 2,000 Hz was utilized. This resulted in a database of 17 pressure measurements originating from six different Titan IV flights. Data were used from Titan IV flights K-1 (2 measurements), K-4 (6), K-10 (3), K-21 (3), K-19 (2) and K-23 (1).

All six of these Titan IV flights were launched from the NASA Kennedy Space Center's Eastern Test Range (ETR). Flights K-1, K-4 and K-19 were launched from Launch Complex (LC) 41. Flights K-10, K-21 and K-23 were launched from LC-40. All these launches occurred from 1989 to1995. The flight data used in this paper were obtained from the official Martin Marietta Company (now Lockheed Martin Corporation) reports (References [**44**], [**45**], [**46**], [**47**], [**48**], [**49**]).

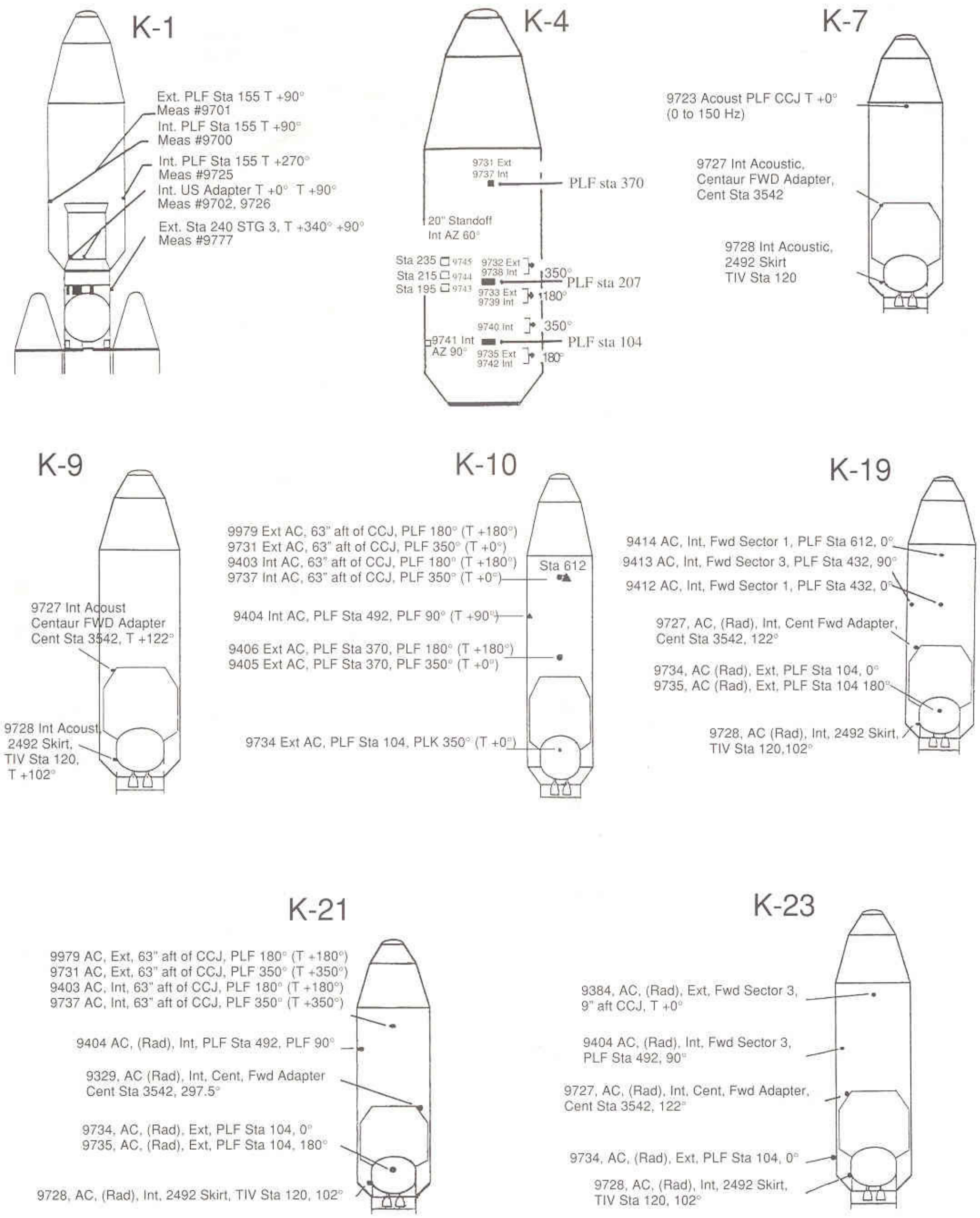

Figure 2. Location of microphones used on eight Titan IV flights to derive Cassini acoustic criteria.

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Figure 4-4: **Locations of microphones on eight Titan IV flights (from Reference [34])**

Appendix **A** contains the Titan IV liftoff acoustic database used in this study. The sound pressure levels (SPL) in decibels (dB re 20 μPascals) are listed in Tables **A-1, A-2,** and **A-3** as a function of OTOB center frequencies for each of the six Titan IV flights and 17 internal payload fairing microphones. Figures **A-1**, **A-2, A-3**, **A-4**, **A-5**, and **A-6** illustrate the spectral shape of these SPL levels for each of these Titan IV flights.

Table **4-1** shows the mean, standard deviation and maximum at each of the OTOB center frequencies for this collection of data.

Figure **4-5** shows all 17 SPL measurements plotted together. It is from this collection of data that test levels will be derived to set MEE and EEE levels. The mean, using a straight numerical average of the dB levels at each frequency, is also plotted in Figure **4-5**.

Table 4-1: **Statistics of Titan IV Flight Database(17 Data Measurements)**

Frequency (Hz)	**Mean ($\bar{X}$)** **SPL** (dB)	**Std Dev(s_x)** **SPL** (dB)	**Maximum** **SPL** (dB)
20.0	109.7	5.1	122.2
25.0	113.7	2.9	118.6
31.5	117.9	3.6	125.2
40.0	120.0	4.5	133.2
50.0	120.2	3.2	128.9
63.0	120.7	3.5	127.2
80.0	123.0	3.1	128.9
100.0	124.0	2.9	129.2
125.0	124.7	2.4	129.7
160.0	126.0	3.8	130.9
200.0	126.5	3.5	131.7
250.0	127.8	3.2	134.0
315.0	122.9	2.8	126.9
400.0	115.3	3.4	123.3
500.0	110.9	3.7	120.6
630.0	108.5	4.0	118.5
800.0	108.6	4.3	118.1
1000.0	110.0	3.4	118.2
1250.0	109.4	2.7	113.5
1600.0	108.5	3.4	114.5
2000.0	108.8	4.1	116.0
Overall SPL	134.6		141.1

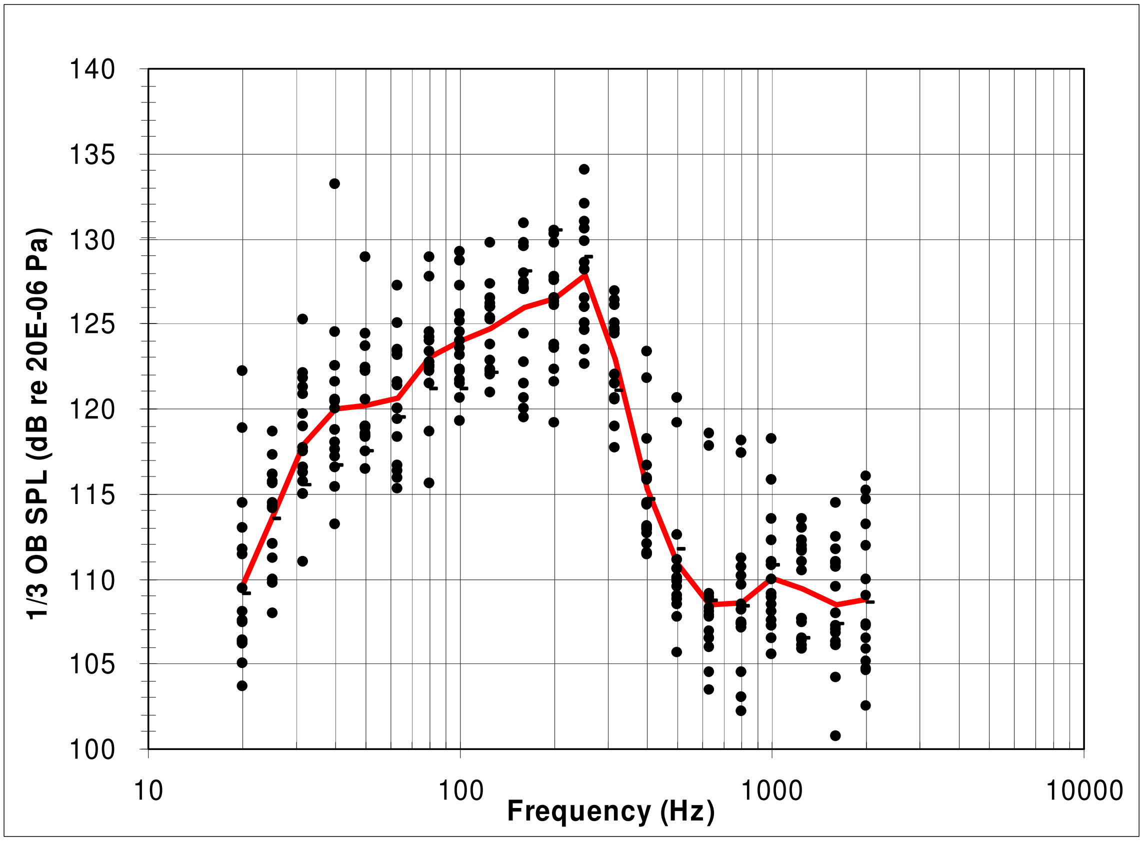

Figure 4-5: **Maximax Acoustic Spectra for Titan IV Flight Database for Internal Payload Fairing Measurements during Liftoff showing Mean Level (red line)**

Chapter 5

Application of the Normal Tolerance Limit Method

5.1 Applying the NTL

Applying the one-sided NTL method to this Titan IV dataset is straightforward. The number of data samples, n, is 17. Referring to Table 2-1 the K factors for NTL (n=17, β=0.95, γ=0.50) is 1.68, and for NTL (n=17, β=0.99, γ=0.90) is 3.14. For this analysis the K factors from Reference [5] were actually used to obtain more accuracy and were respectively 1.676 and 3.137.

Knowing the K factor, and the mean and standard deviation of the data at each OTOB, application of the NTL definition (Eq. 2.1) repeated here

$$NTL_x(n,\beta,\gamma) = \overline{X} + (K_{n,\beta,\gamma} \times s_x) \qquad \textbf{5.1}$$

yields the results shown in Table 5-1 and Table 5-2 for P95/C50 and P99/C90 respectively.

Table 5-1: **NTL results for P95/50 (K=1.676)**

Frequency (Hz)	**Mean ($\overline{X}$) SPL** (dB)	**Std Dev (s_x) SPL** (dB)	**NTL 95/50** (dB)
20.0	109.7	5.1	118.3
25.0	113.7	2.9	118.6
31.5	117.9	3.6	123.9
40.0	120.0	4.5	127.6
50.0	120.2	3.2	125.5
63.0	120.7	3.5	126.6
80.0	123.0	3.1	128.2
100.0	124.0	2.9	128.8
125.0	124.7	2.4	128.7
160.0	126.0	3.8	132.3
200.0	126.5	3.5	132.4
250.0	127.8	3.2	133.2
315.0	122.9	2.8	127.5
400.0	115.3	3.4	121.0
500.0	110.9	3.7	117.2
630.0	108.5	4.0	115.1
800.0	108.6	4.3	115.7
1000.0	110.0	3.4	115.7
1250.0	109.4	2.7	114.0
1600.0	108.5	3.4	114.2
2000.0	108.8	4.1	115.7
Overall SPL	134.6		140.2

Table 5-2: **NTL results for P99/90 (K=3.137)**

Frequency (Hz)	**Mean ($\overline{X}$) SPL** (dB)	**Std Dev (s_x) SPL** (dB)	**NTL 99/90** (dB)
20.0	109.7	5.1	125.8
25.0	113.7	2.9	122.8
31.5	117.9	3.6	129.2
40.0	120.0	4.5	134.1
50.0	120.2	3.2	130.2
63.0	120.7	3.5	131.7
80.0	123.0	3.1	132.8
100.0	124.0	2.9	133.1
125.0	124.7	2.4	132.2
160.0	126.0	3.8	137.8
200.0	126.5	3.5	137.5
250.0	127.8	3.2	137.9
315.0	122.9	2.8	131.6
400.0	115.3	3.4	126.0
500.0	110.9	3.7	122.6
630.0	108.5	4.0	120.9
800.0	108.6	4.3	122.0
1000.0	110.0	3.4	120.7
1250.0	109.4	2.7	118.0
1600.0	108.5	3.4	119.1
2000.0	108.8	4.1	121.6
Overall SPL	134.6		145.1

5.2 Discussion of NTL Results

The assumption in using the NTL method is that the data come from a normal distribution. In this case, it is assumed that the SPL data (in dB) are normally distributed. If this is not the case, the resulting limits are probably in error.

The P95/C50 level represents the MEE or maximum expected environment. Figure **5-1** shows the NTL P95/C50 level plotted with the 17 data measurements, along with the mean level.

On average (C50) one would expect 95 percent (P95) of the data to be at or below this P95/C50 level. There are 23 data points that actually exceed the P95/C50 level. (Five OTOBs have no exceedence, nine OTOB have one exceedence, and seven OTOBs have two exceedences.) Since there are 357 data points in total (17 microphones x 21 OTOB frequencies) that means that for this particular data set there is (357-23)/357 or 93.6 percent of the data are actually at or below this P95/C50 level. Although not perfect, this is reassuring that the P95/C50 level is performing as expected. The slight difference may be due to the assumption that the SPL dB data are normally distributed, or it may simply be due to the randomness of the events themselves.

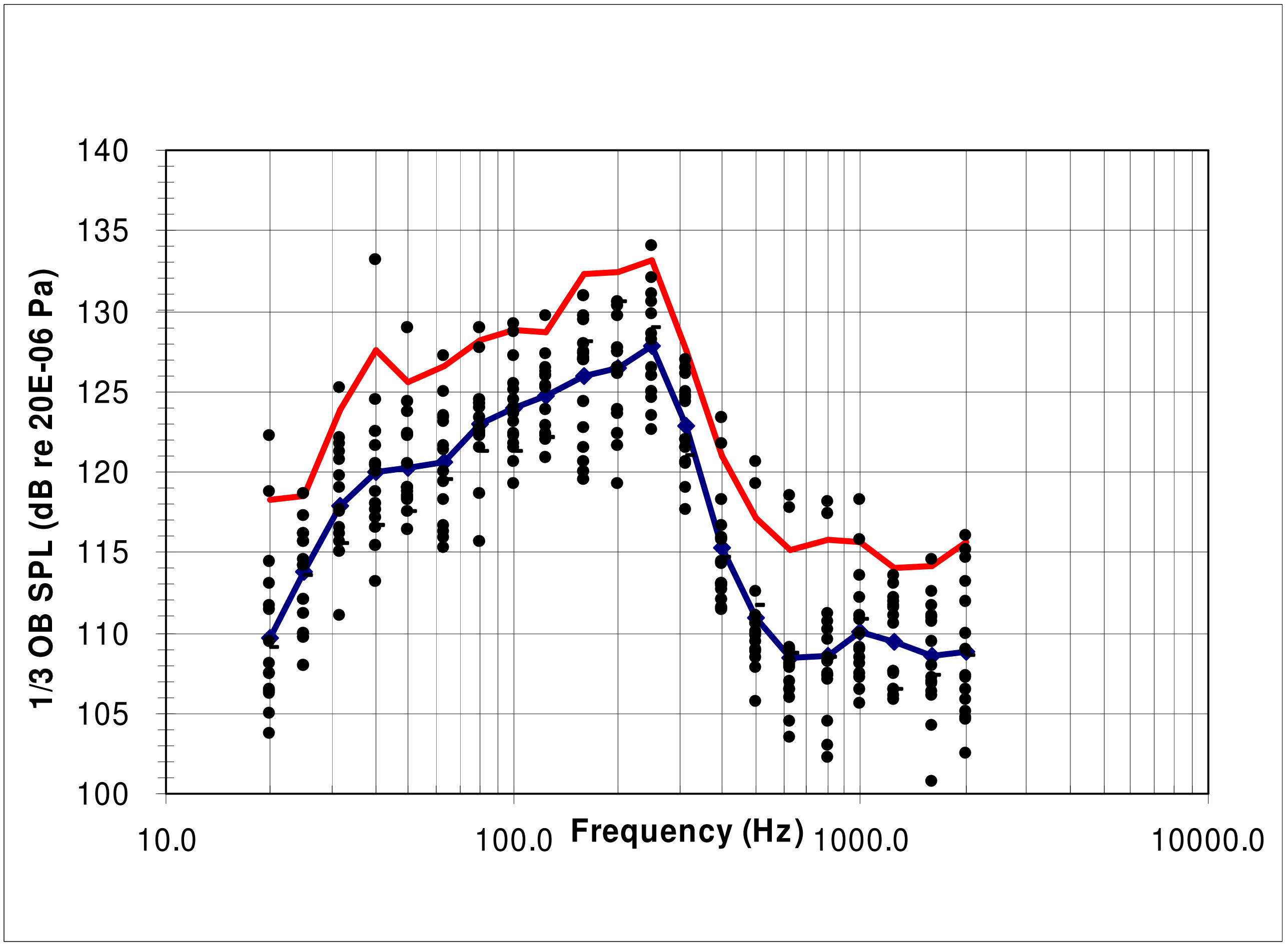

Figure **5-1**: **Acoustic Spectra for Titan IV ETR Flight Database for Internal Payload Fairing Measurements during Liftoff showing**
NTL P95/C50 (top red line) and Mean Levels (bottom blue line)

For this particular data set, the P99/C90 level should encompass all (or almost all) the flight data if it behaves as expected. Figure **5-2** shows the NTL P99/C90 level, along with the 17 sets of data, the NTL P95/C50 and the mean levels.

Per Reference [20] for P99/C90 “there is 1 chance in 10 of exceeding the level once in 100 flights.” Since for this data set we have 357 “flights” the odds are that no flight data should exceed the calculated NTL P99/C90 level. Figure 5-2 indeed bears this out.

This identifies an advantage of using the NTL P99/C90 level as a qualification test level. The design of the spaceflight hardware will be tested (i.e. qualified) to levels that it should rarely see in flight. Note however that there is one data point at 40 Hz whose level does approach the NTL P99/C90 level. The disadvantage of using the NTL P99/C90 level, of course, is the higher test levels may be over-conservative. In this particular case, the P99/C90 levels are anywhere from 7.4 to 16.1 dB above the mean of the data depending on the OTOB frequency, with an average of 11 dB above the mean.

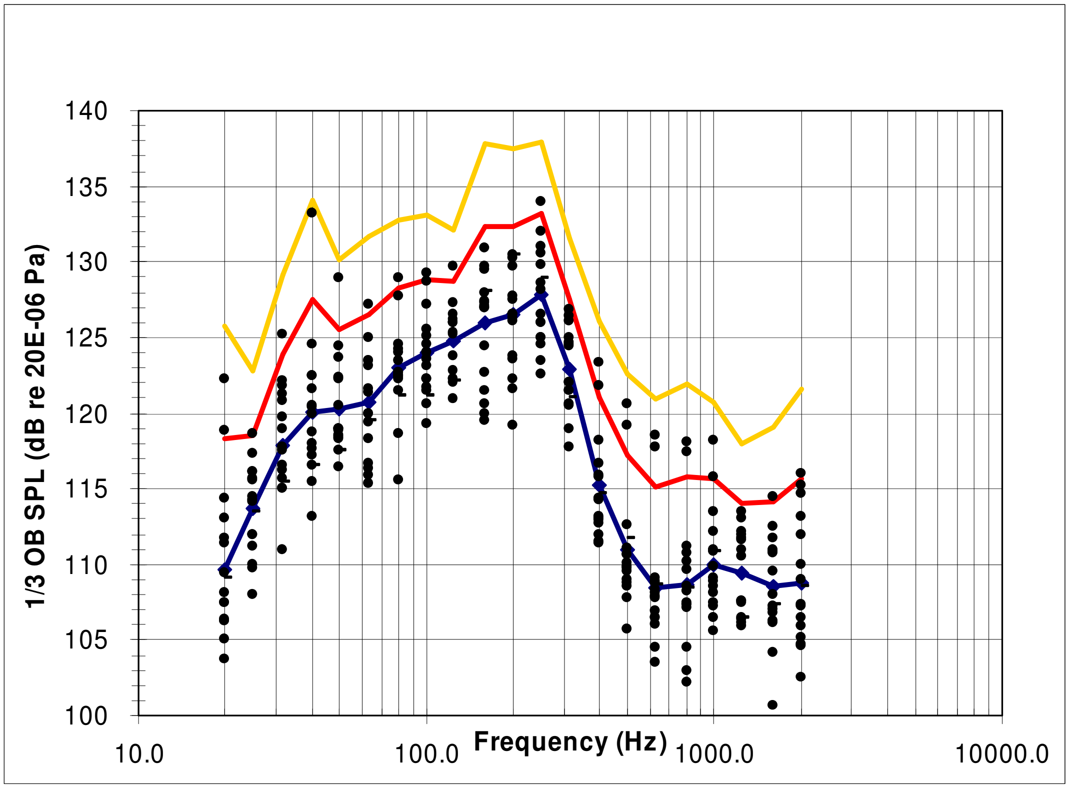

Figure 5-2: **Acoustic Spectra for Titan IV ETR Flight Database for Internal Payload Fairing Measurements during Liftoff showing**
NTL P99/C90 (top gold line), NTL P95/C50 (middle red line) and Mean (lower blue line) Levels

Chapter 6

Application of the Bootstrap Method

6.1 Applying the Bootstrap Method

The Bootstrap method was implemented through the use of MATLAB coding. This code is provided in Appendix B. It was modified from a MATLAB bootstrap code written by Paez (Reference [50]). The modifications were made to enable the code to generate the statistics of interest for this paper, namely the bootstrap "equivalent" to the NTL P95/C50 and P99/C90 levels.

In lieu of a NTL K factor, the bootstrap (BS) equivalent P95/C50 and P99/C90 levels were computed by using the bootstrap replicates of the statistics of interest themselves.

The statistics of interest for this Bootstrap analysis are the P95 and P99 probability levels. This requires that the bootstrap mean and bootstrap standard deviation be jointly used as a bootstrap pair to compute the desired probability (P) level. In the MATLAB code at each OTOB frequency, a bootstrap sample is drawn that consists of 17 data points randomly selected (with replacement) from the original 17 Titan IV acoustic SPL data points. Next the mean and standard deviation of this bootstrap sample are computed. This process of creating bootstrap samples and generating the bootstrap replicates for the statistics of interest is repeated numerous (nr) times.

As explained in Section 3.2, Steps 5 and 6, the cumulative distribution function (CDF) formed by the bootstrap replicates could be utilized to generate confidence intervals of the mean value. This is straightforward for easily found statistic of interest such as the mean or standard deviation. For example, one could use the Bootstrap process to confidently state that 80 percent of the time the mean of the data would be between the values associated with the 10 percent and the 90 percent values of the bootstrap replicate CDF. For this paper the statistic of interest is not just the mean and standard deviation but instead the values generated by these that are associated with the P95 and P99 probability levels.

6.2 Calculation of Probability

One could simply calculate the mean value of the nr bootstrap replicate's means and the mean value of the nr bootstrap replicate's standard deviations, and use these values with the previously described NTL K factor associated with the P95/C50 and P99/C90 levels to determine the new equivalent bootstrap P/C levels. However that method would once again presume that the underlying data distribution was normal. Furthermore it is thought that the bootstrap sample data are most accurately used by keeping the pair of the mean and standard deviation values generated in each bootstrap replicate together for analysis of P/C levels. That is, a joint probability distribution would be preferable, rather than handling each of these statistics individually.

It was initially decided to calculate the numerous bootstrap P95 and P99 levels using each bootstrap replicate's mean and standard deviation with the standard normal value for P95 (1.645) and P99 (2.326). This method implies 100 percent confidence or that the number of bootstrap samples is great enough to simulate the entire population (thus justifying the use of the standard normal probability value instead of the K factor). Although this approach has the advantage of jointly using the information generated by the bootstrap replicates to calculate the P95 and P99 levels, it still has the significant disadvantage of assuming a normal distribution.

Finally it was decided to use the distribution of the original sample data itself to describe the CDF of the data. To do this the original set of the 17 flight data measurements were converted to standardized format for each OTOB frequency. This z-value was calculated by taking each data point and first subtracting out the sample mean, and secondly by dividing by the sample standard deviation, as shown in Eq. **6.1**.

$$z_i = \frac{x_i - \overline{X}}{s_x} \qquad \textbf{6.1}$$

For example,

Original data for K-1 Microphone 9700 at 20 Hz = 106.2 dB (from Table **A-1**)

Sample mean of all original data at 20 Hz = 109.7 dB (from Table **5-1**)

Sample standard deviation of all original data at 20 Hz = 5.1 dB (from Table **5-1**)

Then the z-score for this example is calculated in Eq. 6.2 as,

$$z_{K-1\ 9700,\ 20} = \frac{106.2 - 109.7}{5.1} = -0.686 \tag{6.2}$$

The z-values were calculated for all 17 microphones at all 21 OTOB frequencies. Ideally an individual CDF would be formed from the z-values corresponding to each OTOB frequency. However, due to the limited number (17) of original measurements, this would not provide the necessary resolution required to calculate tail probabilities from the CDF. Therefore it was decided to combine the z-values at all the OTOB frequencies to form the best estimate of the CDF for this entire data set. Doing this created 357 z-values (17 x 21) which does provide enough points (resolution) in the CDF to estimate the P95 and P99 points without extrapolation. Similar approaches of combining data from multiple frequencies have been successfully used for other NASA programs (References [15], [16], [51], and [52]).

Combining the z-values at all OTOB frequencies assume that the probability distribution of the data is the same for all OTOB frequencies. This may be unlikely, but the introduction of this possible error is noted, but accepted as necessary in order to proceed. Some recent work indicates that this assumption may be reasonable (Reference [53]).

Appendix C Tables C-1, C-2, and C-3 provide the z-values for the Titan IV liftoff acoustic SPL (dB) database. This data may be sorted and used to create a histogram, as shown in Figure 6-1 and Table 6-1. Also shown on Figure 6-1 and Table 6-1 is the expected number of occurrences for a theoretical normal distribution of 357 points.

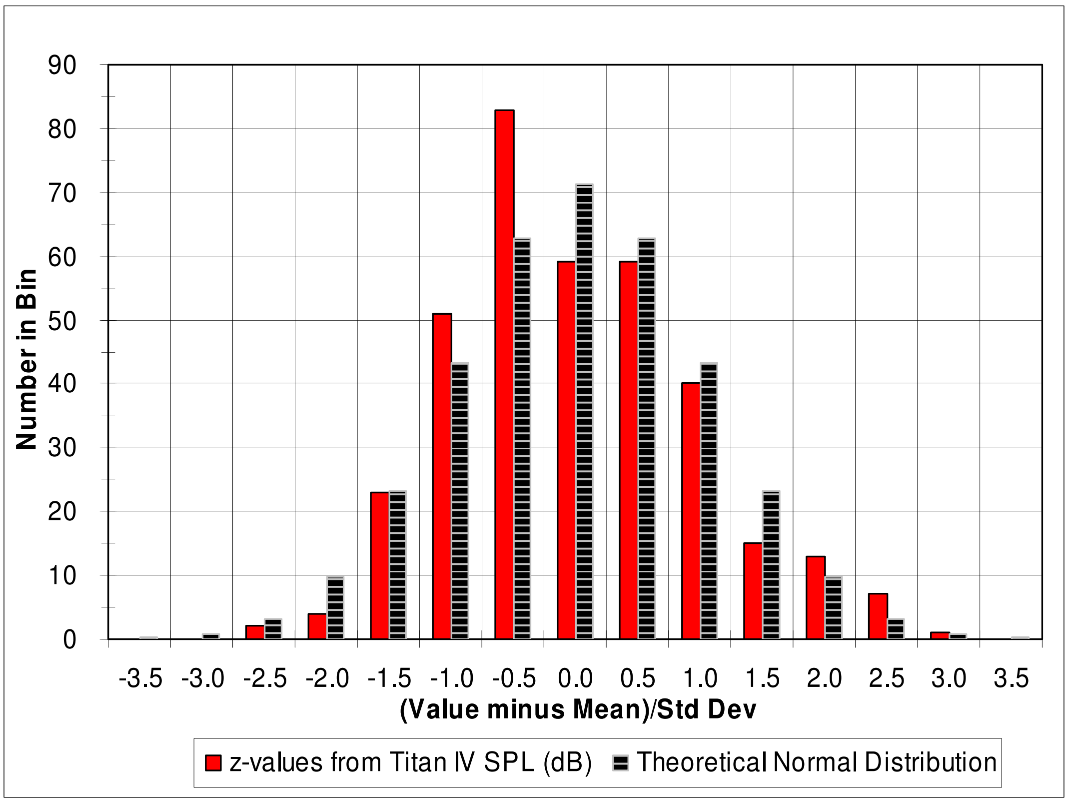

Figure 6-1: **Histogram of z-values from Titan IV Acoustic SPL (dB) Database during Liftoff**

The data appear to come from a source that is non-Gaussian, however, while the comparison of the actual data distribution versus the theoretical normal distribution is not perfect, one can certainly not rule out the possibility that the actual Titan IV SPL data did come from a normal distribution.

Table 6-1: **Histogram Data of z-values from Titan IV acoustic SPL database (bins are +/- 0.25 around center)**

Bin Center	Number in Bin from z-values of Titan IV SPL (dB) database	Number in Bin from Theoretical Normal Distribution
-3.5	0	0.2
-3.0	0	0.8
-2.5	2	3.1
-2.0	4	9.6
-1.5	23	23.1
-1.0	51	43.2
-0.5	83	62.8
0.0	59	71.2
0.5	59	62.8
1.0	40	43.2
1.5	15	23.1
2.0	13	9.6
2.5	7	3.1
3.0	1	0.8
3.5	0	0.2

Table 6-2 provides some further statistics for the z-values from the Titan IV acoustic SPL database. The median, standard deviation and excess kurtosis certainly look representative of a normal distribution. The skewness of this data set, characterizing the degree of asymmetry of the distribution about its mean, does seem a bit high for normal data (Reference [54]). Perhaps this is due to the combining the z-values over all the OTOB frequencies, since this statistic (and other higher moments) are sensitive to small deviations from normal. A positive value of skewness indicates a distribution whose tail extends toward the positive values. The kurtosis of a data set characterizes the relative peakedness or flatness of the distribution relative to a normal distribution. A standard normal distribution would have a kurtosis of three. The excess kurtosis is that amount above the standard normal kurtosis value of three, and thus would be zero for a standard normal distribution. Eq. 6.3 and Eq. 6.4 gives the equations used to calculate the skewness and excess kurtosis respectively.

$$Skewness = \frac{n}{(n-1)(n-2)} \sum_{i=1}^{n} \left(\frac{x_i - \overline{X}}{s_x} \right)^3 \tag{6.3}$$

$$Excess\ Kurtosis = \left\{ \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum_{i=1}^{n} \left(\frac{x_i - \overline{X}}{s_x} \right)^4 \right\} - \frac{3(n-1)^2}{(n-2)(n-3)} \tag{6.4}$$

Table 6-2: **Additional Statistics of z-values from Titan IV acoustic SPL database**

Number of data points	357
Median	-0.098
Standard Deviation	0.972
Skewness	0.431
Excess Kurtosis	0.008

The cumulative distribution function (CDF) for the Titan IV acoustic SPL database was formed from the z-values and plotted in Figure 6-2 versus a theoretical normal distribution. Because of the smoothing inherent in the computation of the empirical CDF the Titan IV data appear to be close to normal.

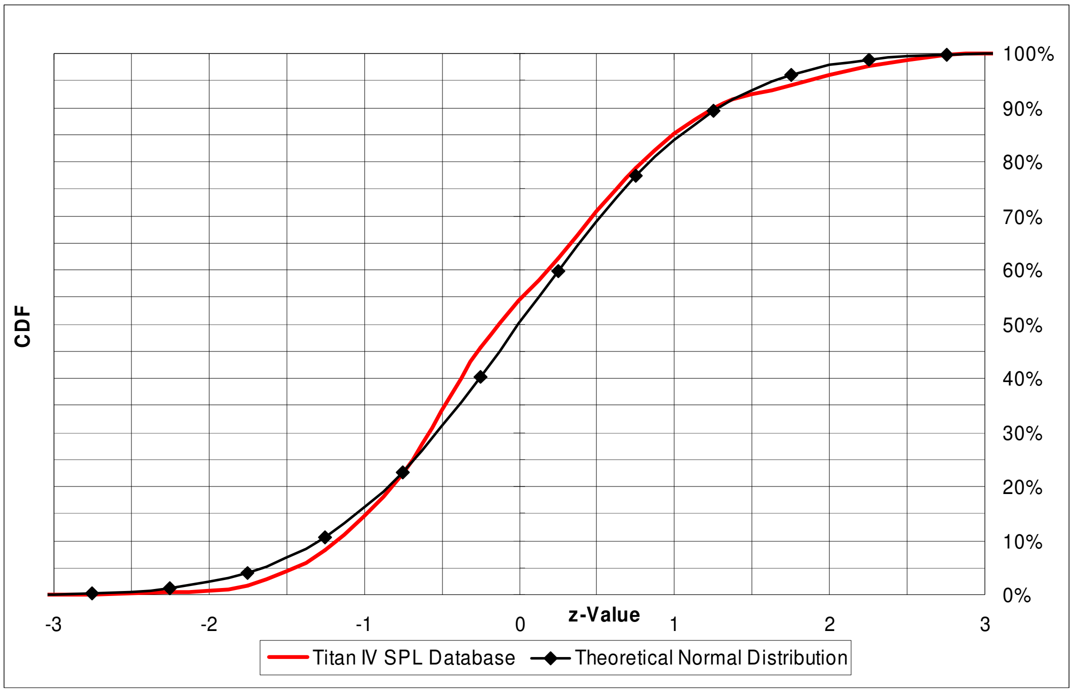

Figure 6-2: **Comparison of Cumulative Distribution Function for z-values from Titan IV SPL Database and Theoretical Normal Distribution**

This Titan IV CDF was used to find the z values for CDF values of P95 and P99. This is shown in Table 6-3 versus the theoretical normal values.

Table 6-3: **Probability Values derived from CDF**

Level	Titan IV Database	Theoretical Normal
P50 (mean)	-0.9826	0.0
P95	1.786	1.645
P99	2.481	2.326

The P95=1.786 and P99=2.481 are the z-values used in the MATLAB code for this Titan IV dataset. For each bootstrap sample the following levels are computed,

P95 = bootstrap replicate mean + (1.786 $\times$ bootstrap replicate standard deviation)

P99= bootstrap replicate mean + (2.481 $\times$ bootstrap replicate standard deviation)

One sees that the z-value CDF yielded slightly larger probability values than would the standard normal values.

A large number of bootstrap samples were formed. The effect of the number of bootstrap samples on the accuracy of the estimation will be discussed later in Section **6.5**. Appendix **D** shows the scatter of the bootstrap replicate pair (mean and standard deviation) at each OTOB frequency. These scatter plots show the variability of results from 1000 bootstrap samples. These plots will be discussed later in Section **6.4**.

6.3 Confidence Calculations

At this point, the MATLAB code has calculated nr replicate values of the P95 and P99 levels at each OTOB frequency. To compute the confidence level one simply has to sort these values, and then select the particular confidence level desired as the percentage point of the approximate sampling distribution of the P95 or P99 random variable.

For example, if nr=1000, and one wanted the bootstrap equivalent for the P95/C50 level, one would sort in order (lowest to highest) the 1000 bootstrap replicate calculations of the P95 level (as obtained per Section **6.2**). The 50 percent confidence would thus be the $0.50 \times 1000 = 500^{th}$ value (for this example) of the sorted P95 bootstrap levels. This computation would be done at each OTOB frequency.

Likewise for the P99/C90 level, one would find the 900^{th} value (out of 1000 for this example of nr=1000) of the sorted P99 bootstrap replicates.

6.4 Bootstrap Results and Discussion

The results generated through this Bootstrap method are summarized in Table **6-4** for the case with 1000 bootstrap samples (nr=1000) for both the P95/C50 and P99/C90.

Table 6-4: **Bootstrap (BS) equivalent P95/C50 and P99/C90 Levels for nr=1000**

Frequency (Hz)	BS Mean SPL (dB)	BS Std Dev SPL (dB)	BS 95/50 (dB)	BS 99/90 (dB)
20.0	109.6	4.8	118.2	126.0
25.0	113.7	2.8	118.6	121.9
31.5	117.9	3.5	124.0	128.7
40.0	120.0	4.3	127.7	134.8
50.0	120.2	3.0	125.6	130.5
63.0	120.7	3.4	126.8	130.8
80.0	123.0	2.9	128.3	132.4
100.0	124.0	2.8	129.0	132.6
125.0	124.7	2.3	128.8	131.7
160.0	126.0	3.6	132.5	136.3
200.0	126.5	3.4	132.5	136.4
250.0	127.8	3.1	133.3	137.3
315.0	122.9	2.6	127.7	130.7
400.0	115.2	3.3	121.2	126.4
500.0	111.0	3.5	117.4	123.5
630.0	108.4	3.7	115.4	121.8
800.0	108.6	4.0	115.9	122.2
1000.0	110.0	3.2	115.9	120.7
1250.0	109.4	2.6	114.1	116.9
1600.0	108.6	3.2	114.4	118.6
2000.0	108.8	3.9	116.0	120.9
Overall SPL	134.7		140.3	144.5

Figure 6-3 shows the bootstrap P95/C50 result for nr=1000 plotted with all original 17 flight data measurements and the original sample data mean. This P95/50 level would represent the MEE or maximum expected environment. As before (for the NTL P95/C50 level), one would expect on average (C50) that 95 percent (P95) of the data would be at or below this level. It turns out that there are 20 points that exceed the bootstrap (BS) P95/50 level (six OTOB frequencies have no exceedences, ten OTOB have one exceedence, and five OTOB have two exceedences). This leads to (357-20)/357 = 94.4 percent of the data being at or below this level. This favorably compares to the 93.6 percent result from the NTL P95/C50 level as described in Section 5.2. A closer inspection of these data shows that the difference between the 23 exceedences of the NTL level and the 20 exceedences of the bootstrap level is due to changes on the order of 0.2 dB which are considered insignificant.

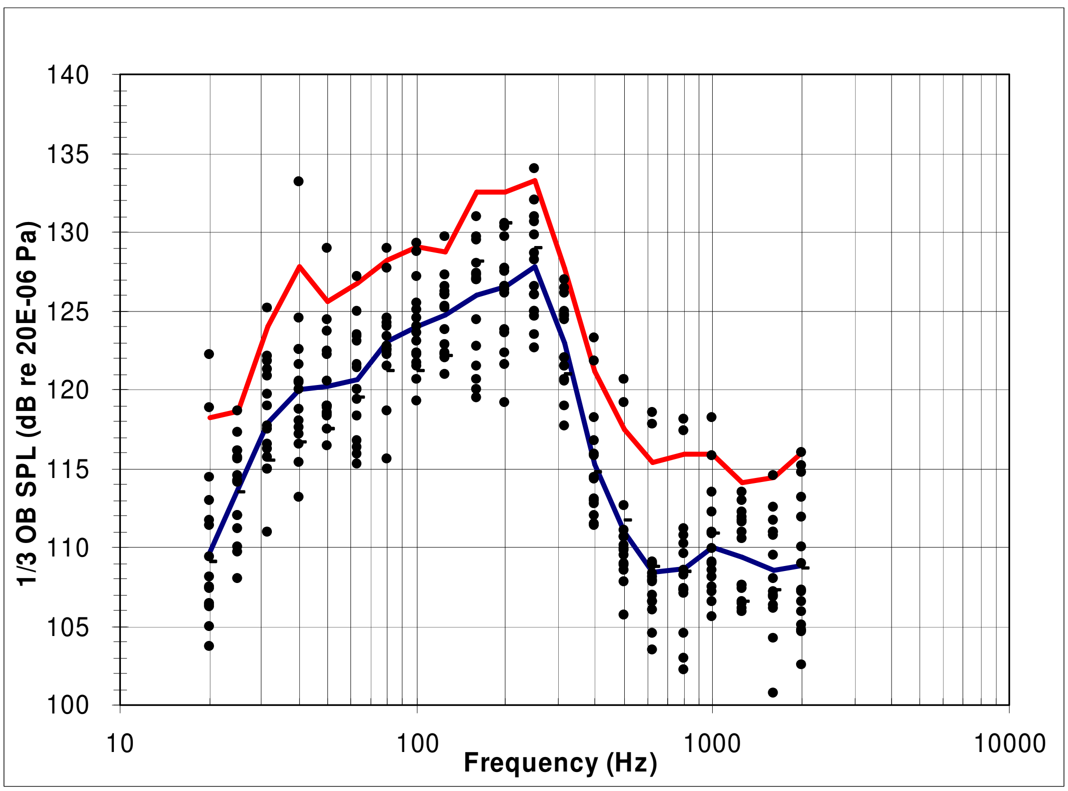

Figure 6-3: **Maximax Acoustic Spectra for Titan IV Flight Database for Internal Payload Fairing Measurements during Liftoff showing Bootstrap P95/C50 Level (top red line) and Mean Level (bottom blue line)**

Figure 6-4 shows the Bootstrap P99/C90 result for nr=1000, again plotted with the Bootstrap P95/C50, the sample mean and the original flight data. Again one would expect to see no exceedences to the P99/C90 level, and that is indeed true for this specific analysis.

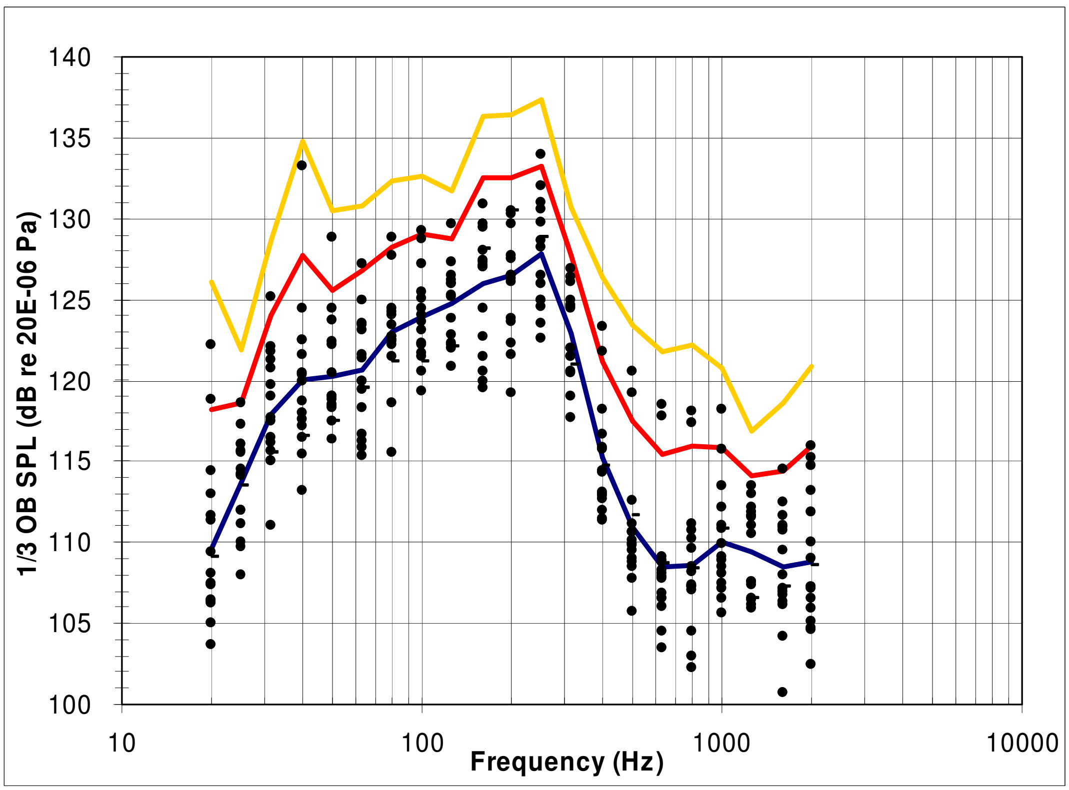

Figure 6-4: **Maximax Acoustic Spectra for Titan IV Flight Database for Internal Payload Fairing Measurements during Liftoff showing <u>Bootstrap P99/C90 (top gold line) and P95/C50 (middle red line) Levels and Mean (bottom blue line) Level</u>**

It appears that the Bootstrap method provides similar results than the NTL method for this particular data set. The advantage of using the Bootstrap method is that it makes no assumptions on the distribution of the underlying data. The disadvantage is the increased computational effort. The MATLAB runtimes are very short, on the order of seconds and minutes depending on the number of bootstrap samples (nr), however there is setup time involved which is long compared to the "hand-like" calculation time of the NTL method.

The bootstrap scatter plots provided in Appendix **D** deserve some explanation. The various "shapes" that these plots take seem to be related to the range, standard deviation and uniformity of the original sample data. For example, the 17 data points at 125 Hz or at 315 Hz have a relatively small sample standard deviation and small sample range. This results in the scatter plot being roughly circular and "uniform." As the sample standard deviation and sample range of the data gets bigger, as it does at 20 Hz, 400 Hz and 2000 Hz the shape of the scatter plot tends to take on a positively sloping "line" group. Finally a 3rd shape consisting more of families of arcs progressing along a positively sloping line is seen for frequencies like 40 Hz, 500 Hz and 630 Hz. For this grouping the original sample data seems to have one or two "outliers" that can "distort" the bootstrap samples. It is thought that the various arc families relate to the number of times that outlier(s) are or are not included in the bootstrap samples.

Future investigation may lead to use of these bootstrap scatter group shapes to identify outlying data which might in turn lead to deeper investigations into the quality of the measured data, or into decisions as to what data should properly be combined to form an analysis data set.

6.5 Affect of the Number of Bootstrap Samples

As mentioned in Section 3.1 the number of bootstrap samples required depends upon how the bootstrap results will be used. For simple estimation of standard errors as few as 100 samples might suffice. But for accurate confidence estimates the literature says a few thousands samples might be needed.

To investigate this question for this particular problem and data set, bootstrap predictions for the P95/C50 and P99/C90 levels were done using nr values of 50, 500, 1000, 5000 and 50000. As shown in Appendix E Tables E-1 and E-2, both the bootstrap mean and bootstrap standard deviation converged quite rapidly to the sample (17 measurements) mean and standard deviation. Using nr=50 gets close, and a using nr=500 would easily meet the goal of matching the sample mean. A good bootstrap match for the standard deviation was easily achieved with a nr of 500 or 1000.

Similarly Appendix E Tables E-3 and E-4 show how quickly the P95/C50 and P99/C90 levels converge. For the accuracy required (for acoustic SPL in dB) the results barely change after nr=500. Certainly it appears, at least for this particular data set, that using nr=1000 is sufficient.

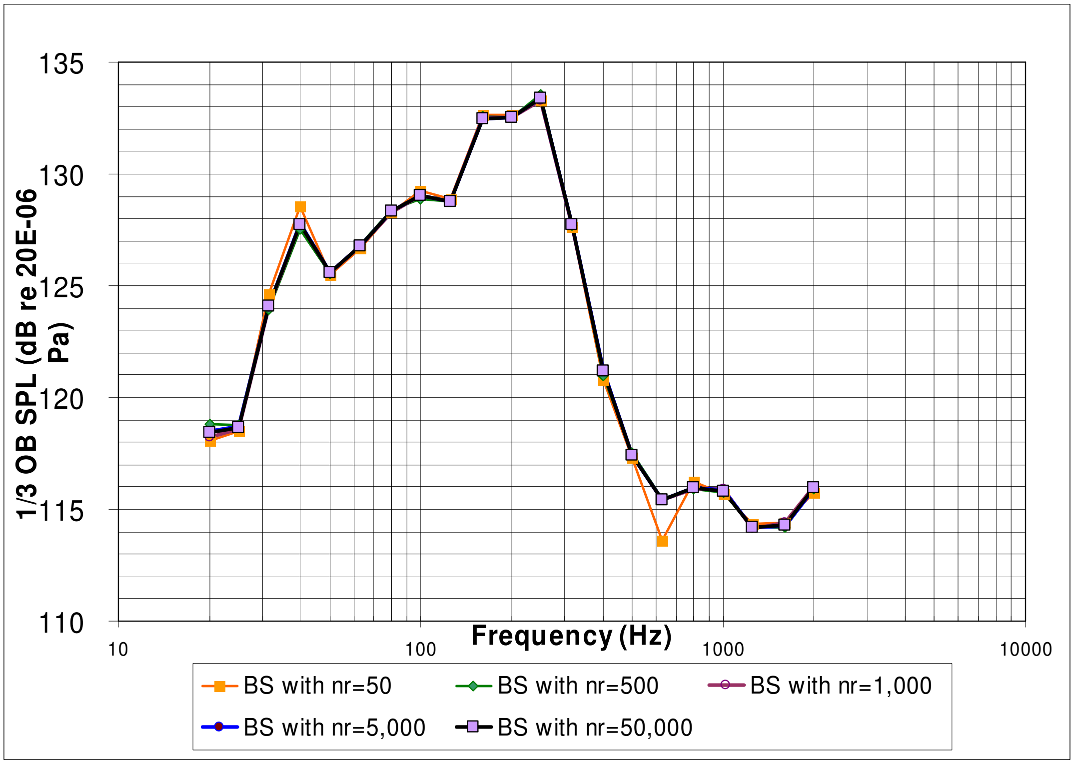

Figure 6-5: **Bootstrap P95/C50 Acoustic Spectra Levels derived from Titan IV SPL (dB) Data from Liftoff**

Figure 6-5 and Figure 6-6 show that there is very little difference between the bootstrap P95/C50 and P99/C90 results for the range of nr studied, even when comparing nr=50 results with nr=50000. Certainly nr=1000 is sufficient for the purposes of this study.

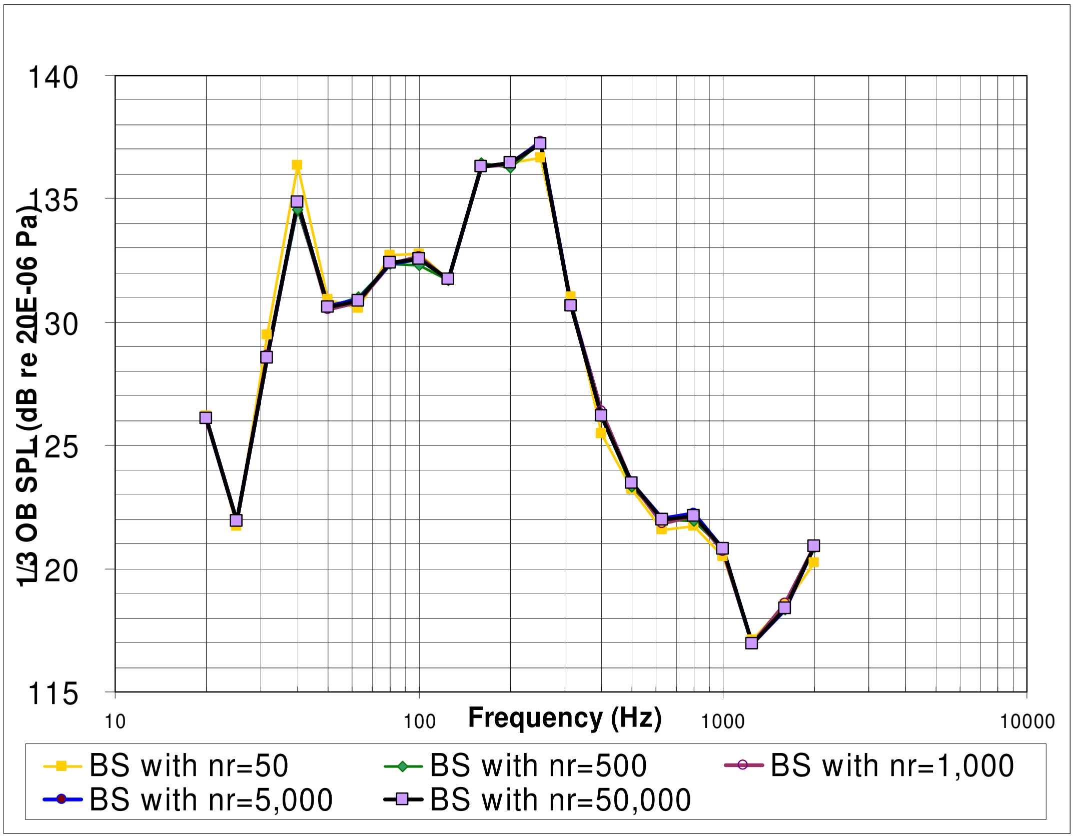

Figure **6-6**: **<u>Bootstrap P99/C90</u> Acoustic Spectra Levels derived from Titan IV SPL (dB) Data from Liftoff**

Chapter 7

Summary

7.1 Comparisons of NTL and Bootstrap Results

The last comparison to make in this paper is that of the NTL results with the Bootstrap results. For this particular data set it turns out that they are extremely close. This is thought to be due to the distribution of the actual data set (z-values of Figure 6-2) being very close to normally distributed, which is what the NTL method assumes.

Figure 7-1 and Table 7-1 show the comparison for the P95/C50 level. There is no significant difference between the results generated by the two methods.

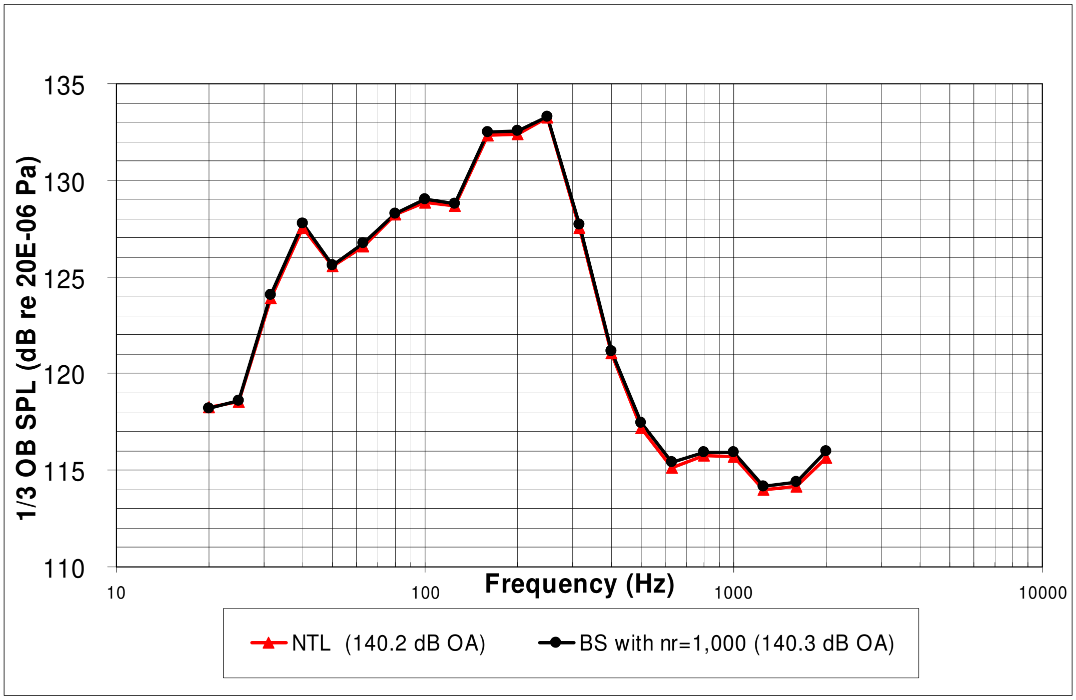

Figure 7-1: **Comparison of P95/C50 Levels computed by NTL and Bootstrap Methods from Titan IV SPL (dB) Data**

Table 7-1: **Comparison of Results for P95/C50**

Frequency (Hz)	**NTL 95/50** (dB)	**BS nr=1000 95/50** (dB)	**Difference 95/50 (dB)**
20	118.3	118.2	0.1
25	118.6	118.6	-0.1
31.5	123.9	124	-0.1
40	127.6	127.7	-0.2
50	125.5	125.6	-0.1
63	126.6	126.8	-0.2
80	128.2	128.3	0
100	128.8	129	-0.2
125	128.7	128.8	-0.1
160	132.3	132.5	-0.2
200	132.4	132.5	-0.2
250	133.2	133.3	-0.1
315	127.5	127.7	-0.2
400	121	121.2	-0.1
500	117.2	117.4	-0.3
630	115.1	115.4	-0.3
800	115.7	115.9	-0.2
1000	115.7	115.9	-0.2
1250	114	114.1	-0.2
1600	114.2	114.4	-0.2
2000	115.7	116	-0.4
OA SPL	140.2	140.3	

Figure 7-2 and Table 7-2 provide this comparison for the P99/C90 levels. There is some visible difference, particularly at 160 to 250 Hz, and at 500 Hz to 630 Hz, but even at these frequencies the levels are within 1.5 dB, and within the test tolerance of most acoustic test chambers. The NTL P99/C90 result tends to be slightly higher, at most but not all frequencies. Both the P99/C90 levels easily envelope the maximum from the original sample data (17 flight data measurements), as expected.

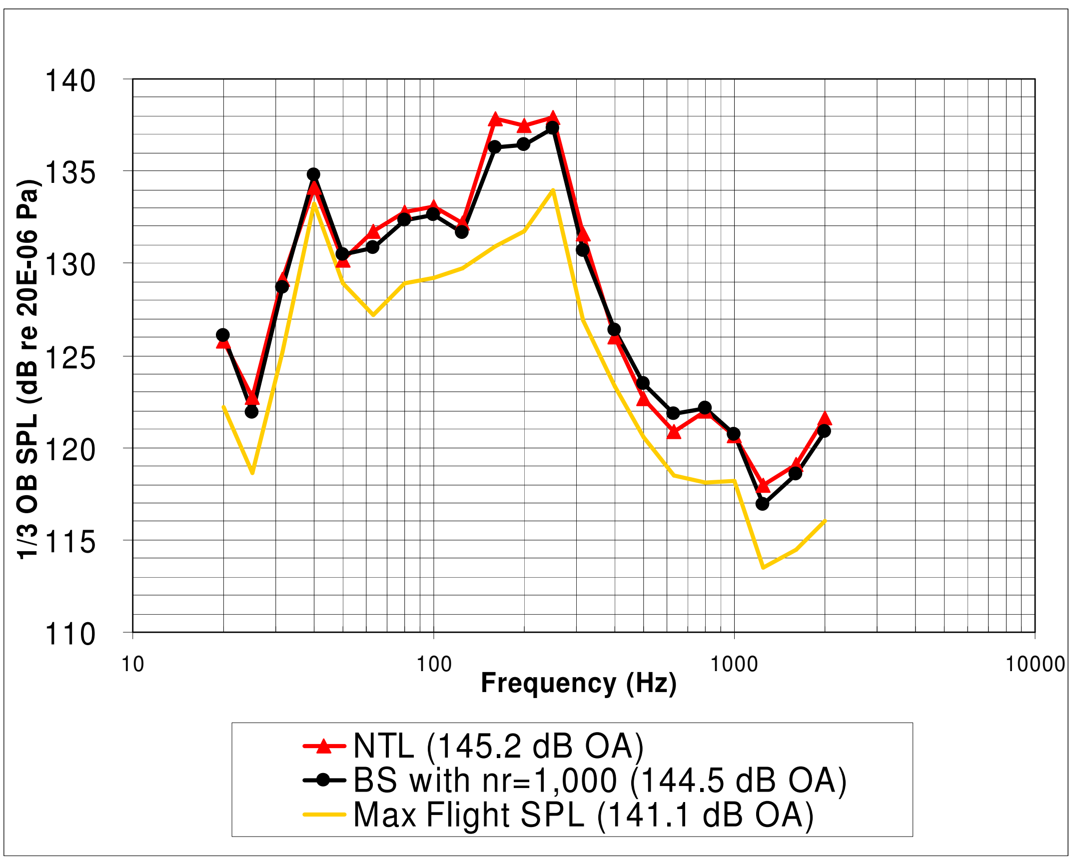

Figure 7-2: **Comparison of <u>P99/C90</u> Levels computed by**
<u>NTL and Bootstrap Methods</u> from Titan IV SPL (dB) Data

Table 7-2: **Comparison of Results for P99/C90**

Frequency (Hz)	**NTL** **99/90** (dB)	**BS nr=1000** **99/90** (dB)	**Difference** **99/90** **(dB)**
20	125.8	126	-0.3
25	122.8	121.9	0.8
31.5	129.2	128.7	0.5
40	134.1	134.8	-0.7
50	130.2	130.5	-0.3
63	131.7	130.8	0.9
80	132.8	132.4	0.4
100	133.1	132.6	0.5
125	132.2	131.7	0.5
160	137.8	136.3	1.5
200	137.5	136.4	1.1
250	137.9	137.3	0.6
315	131.6	130.7	0.9
400	126	126.4	-0.3
500	122.6	123.5	-0.8
630	120.9	121.8	-0.9
800	122	122.2	-0.2
1000	120.7	120.7	0
1250	118	116.9	1
1600	119.1	118.6	0.5
2000	121.6	120.9	0.7
OA SPL	145.2	144.5	

7.2 Conclusions

Two different methods were employed to calculate acoustic levels needed to properly test spaceflight hardware exposed to acoustic loading during launch. The maximum expected environment (MEE) is used as a basis for acceptance testing of flight hardware. The extreme expected environment (EEE) is used for qualification testing of hardware designs.

NASA has traditionally used the one-sided Normal Tolerance Limit (NTL) to define the MEE from available flight data. Recently the AFSSD has recommended using the NTL to also define the EEE levels. MEE is defined as P95/C50, and EEE is defined as P99/C90. By definition the NTL assumes that the data are normally distributed. This assumption has been previously evaluated using aerospace acoustic SPL data and the assumption is generally considered safe for acoustic SPL data in dB. If this assumption is not correct, as for example with random vibration response data, transformation techniques should be employed to accurately use the NTL method.

The Bootstrap Method is a subsampling statistical procedure which uses multiple samples of the original data to allow bootstrap replicate estimates of parameters and confidence intervals to be made. The Bootstrap makes no a priori assumption on the distribution of the data.

Both these methods were applied to the Titan IV acoustic SPL liftoff database consisting of 17 flight acoustic microphone measurements. As shown in this paper, the resulting P95/C50 and P99/C90 levels were remarkably close for these two methods. This is believed to be due at least in part to the apparent normality of the sample flight data utilized. Both methods resulted in (test) levels which perform as expected for MEE and EEE levels.

The fact that these results turned out so close for these two methods provides added confidence in the NTL method approach and results that NASA has traditionally used in the past and continues to use today.

Based on the analysis performed for this paper on this particular flight data set, it appears that both the NTL and Bootstrap methods are valid methods to predict the MEE and EEE level for aerospace acoustic SPL data in dB. The NTL method is well-established within the aerospace industry and is quick to calculate. However, unlike the NTL method, the Bootstrap method does not assume that the sample data come from a normal distribution.

Future investigations comparing these two methods using other data sets may prove informative. Of particular interest would be the application of this analysis to a known non-normal data set to see how the bootstrap results would compare with the NTL results. Examples of this data type might be random vibration response data, shock response spectrum data, or acoustic pressure (in Pascal units, not in dB). If this sort of analysis was performed, it might however be necessary to employ some advanced methods of the Bootstrap such as Efron's BCa method (Reference [**22**]) which adjusts the confidence interval limits based on two factors called the bias-correction and the acceleration.

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Appendix A

Titan IV Liftoff Acoustic Data

(Tables and Plots)

Table A-1: **Liftoff Acoustic Data from Titan IV K-1 and K-4 Flights (interior PLF microphones)**

	K-1		**K-4**					
Type	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT
Station	155	155	370	207	207	104	104	104
Azimuth	90 Deg	270 Deg	350 Deg	350 Deg	180 Deg	350 Deg	90 Deg	180 Deg
Frequency (Hz)	**9700 SPL** (dB)	**9725 SPL** (dB)	**9737 SPL** (dB)	**9738 SPL** (dB)	**9739 SPL** (dB)	**9740 SPL** (dB)	**9741 SPL** (dB)	**9742 SPL** (dB)
20.0	106.2	111.7	103.7	109.1	107.4	108.1	109.4	106.3
25.0	112.0	109.7	111.2	113.5	115.6	117.3	114.2	118.6
31.5	121.8	120.8	111.0	115.5	117.7	117.5	121.3	119.7
40.0	118.0	118.7	117.2	116.6	117.6	116.5	113.2	115.4
50.0	117.5	119.0	118.3	117.5	118.8	120.5	116.4	118.4
63.0	115.3	119.4	123.1	119.5	118.3	116.7	116.3	115.9
80.0	115.6	118.6	124.0	121.2	121.5	122.4	122.2	122.7
100.0	119.3	122.3	125.5	121.2	120.6	122.2	121.7	123.1
125.0	122.2	122.8	125.3	122.1	123.8	120.9	122.3	122
160.0	119.5	120.6	127.3	128.1	124.4	120.0	122.7	121.5
200.0	126.3	121.6	130.3	130.5	123.6	122.3	123.8	119.2
250.0	129.8	124.6	128.2	128.9	123.5	125.0	128.6	122.6
315.0	124.4	126.1	120.5	121.0	117.7	122.0	124.7	119
400.0	121.8	123.3	114.3	114.7	112.9	113.1	115.8	111.4
500.0	119.2	120.6	109.9	111.7	110.6	109.8	110.6	107.8
630.0	117.8	118.5	106.5	108.7	109.1	108.1	108.8	108.3
800.0	118.1	117.4	107.1	108.4	110.2	109.6	111.2	110.7
1000.0	118.2	115.8	108.5	110.8	112.2	108.1	113.5	109.1
1250.0	112.2	111.7	111.6	106.5	111.0	107.4	113.5	105.9
1600.0	109.5	110.7	111.7	107.3	110.9	106.3	114.5	106.8
2000.0	114.7	113.2	107.3	108.6	111.9	107.2	115.2	105.9
Overall SPL	134.5	133.6	135.8	135.4	132.3	132.0	133.8	131.5

Table A-2: **Liftoff Acoustic Data from Titan IV K-10 and K-21 Flights (interior PLF microphones)**

	K-10			K-21		
Type	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT
Station	63 in aft CCJ	492	63 in aft CCJ	63 in aft CCJ	492	63 in aft CCJ
Azimuth	180 Deg	90 Deg	350 Deg	180 Deg	90 Deg	350 Deg
	9403	**9404**	**9737**	**9403**	**9404**	**9737**
Frequency (Hz)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)
20.0	107.5	113.0	105.0	106.4	111.4	103.6
25.0	108.0	112.0	110.0	116.1	114.1	114.8
31.5	115.0	119.0	115.0	116.5	122.1	113.8
40.0	120.0	122.5	120.5	122.5	124.5	121.8
50.0	119.0	118.5	119.0	123.7	124.4	119.3
63.0	123.5	120.0	120.0	127.2	123.4	124.9
80.0	124.5	122.5	122.5	128.9	124.2	126.5
100.0	124.5	124.0	121.5	129.2	128.7	127.5
125.0	126.0	126.0	126.0	129.7	126.5	126.1
160.0	127.0	127.0	128.0	130.9	129.7	130.7
200.0	126.5	126.5	126.5	130.5	129.7	131.7
250.0	125.0	126.0	126.5	130.6	131.0	130.5
315.0	122.0	121.5	121.5	126.9	125.0	125.7
400.0	113.0	111.5	112.0	118.2	115.9	117.8
500.0	109.5	108.5	109.0	112.6	111.1	110.2
630.0	106.5	104.5	106.0	108.9	107.8	106.2
800.0	108.5	104.5	103.0	107.4	107.3	105.4
1000.0	111.0	106.5	107.5	108.9	110.8	106.7
1250.0	113.0	106.5	110.5	111.9	107.6	110.6
1600.0	112.5	107.0	108.0	111.0	106.1	110.4
2000.0	116.0	110.0	109.0	106.5	104.7	107.5
Overall SPL	134.7	134.5	134.4	138.9	137.8	138.0

Table A-3: **Liftoff Acoustic Data from Titan IV K-19 and K-23 Flights (interior PLF microphones)**

	K-19		K-23
Type	PLF INT	PLF INT	PLF INT
Station	432	432	492
Azimuth	0 Deg	90 Deg	90 Deg
	9412	**9413**	**9404**
Frequency (Hz)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)
20.0	118.8	114.4	122.2
25.0	115.7	114.5	116.1
31.5	115.7	116.2	125.2
40.0	121.6	120.4	133.2
50.0	122.4	122.2	128.9
63.0	121.6	121.4	125.0
80.0	123.4	122.7	127.7
100.0	125.1	123.6	127.2
125.0	126.2	125.2	127.3
160.0	127.4	129.5	127.1
200.0	126.1	127.5	127.7
250.0	126.0	134.0	132.0
315.0	120.6	126.4	124.6
400.0	112.7	116.7	114.4
500.0	105.7	110.1	108.8
630.0	103.5	107.9	106.9
800.0	102.2	108.2	107.3
1000.0	105.6	109.9	107.2
1250.0	106.1	106.4	107.6
1600.0	100.7	104.2	107.2
2000.0	102.5	104.6	105.1
Overall SPL	134.9	137.6	139.2

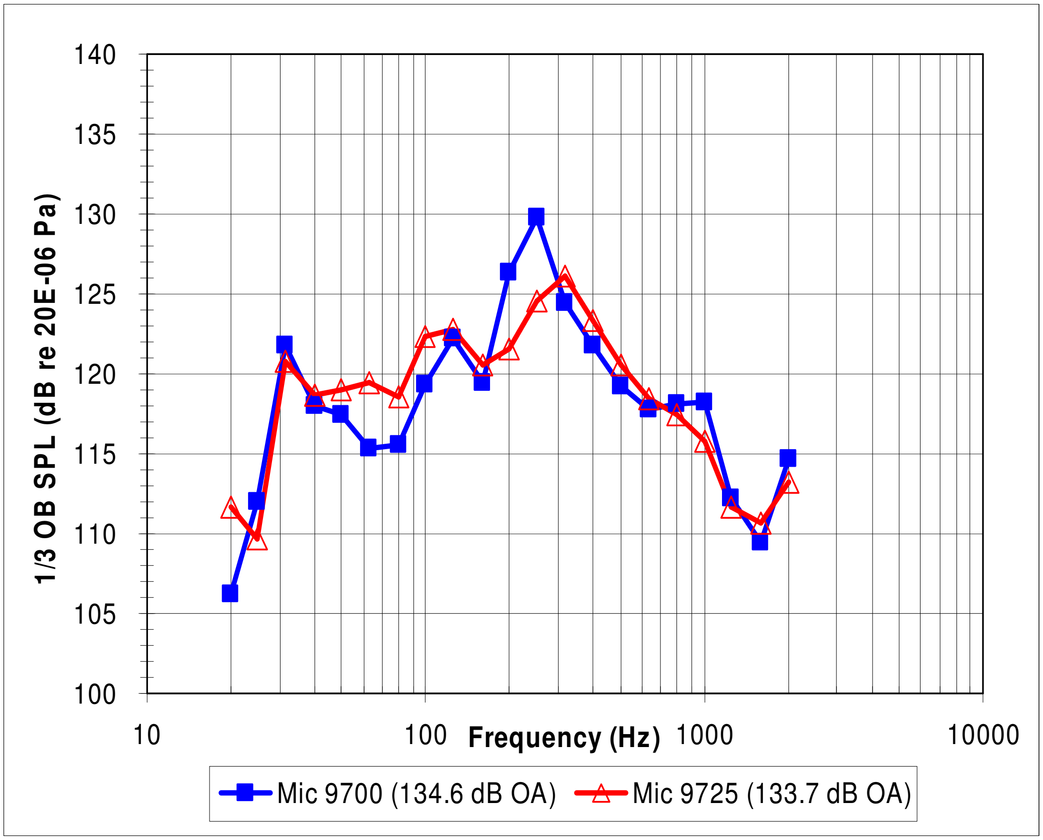


Figure A-1: **Maximax Acoustic Spectra for Titan IV Flight K-1 Internal Payload Fairing Measurements during Liftoff**

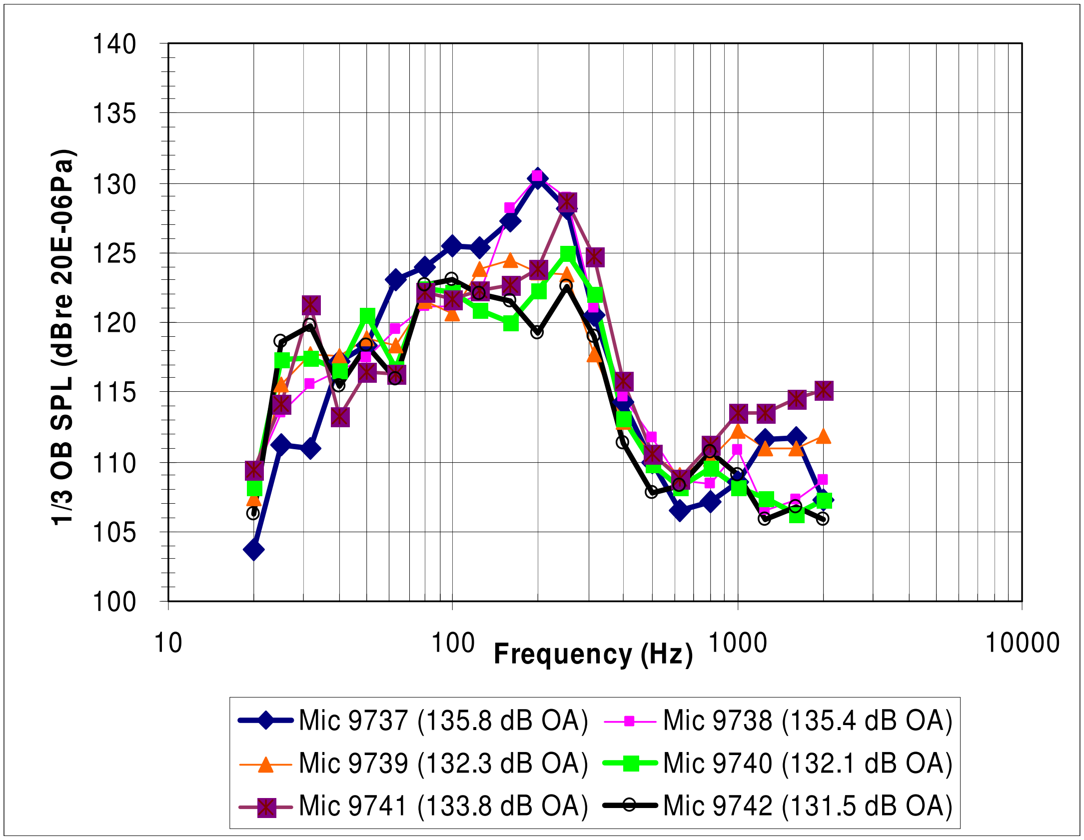


Figure A-2: **Maximax Acoustic Spectra for Titan IV Flight K-4 Internal Payload Fairing Measurements during Liftoff**

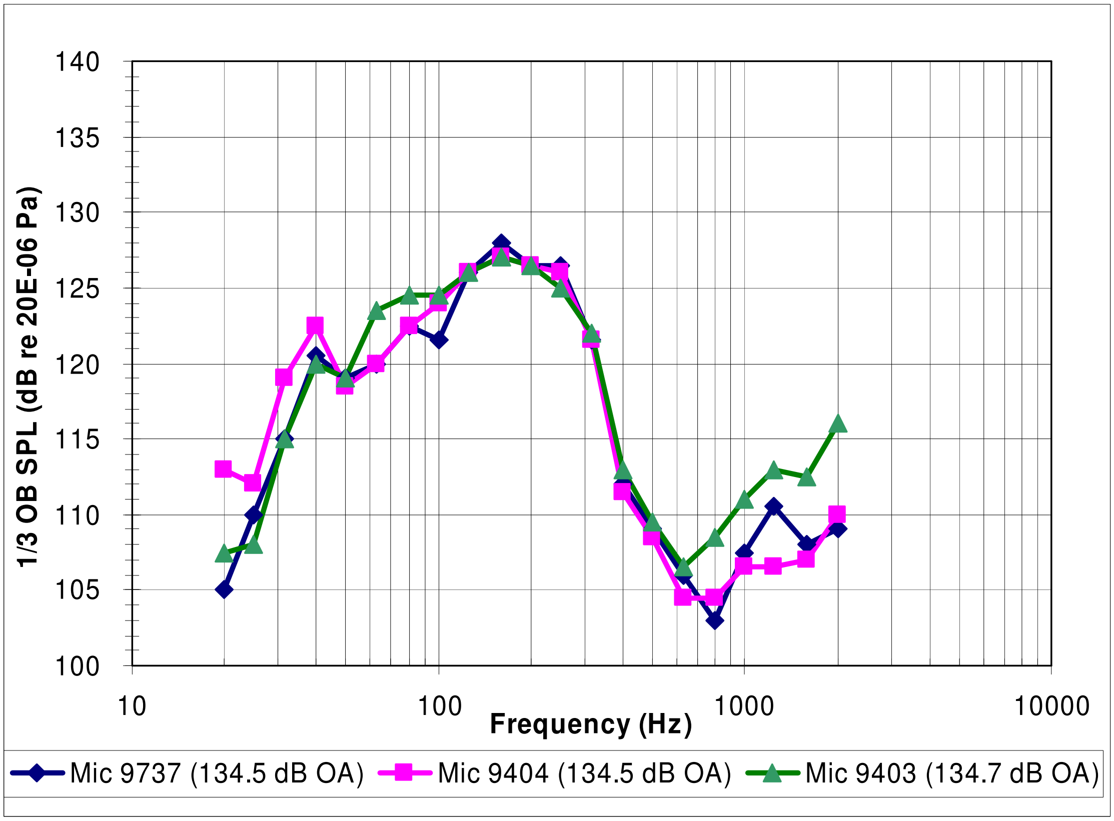


Figure **A-3**: **Maximax Acoustic Spectra for Titan IV Flight K-10 Internal Payload Fairing Measurements during Liftoff**

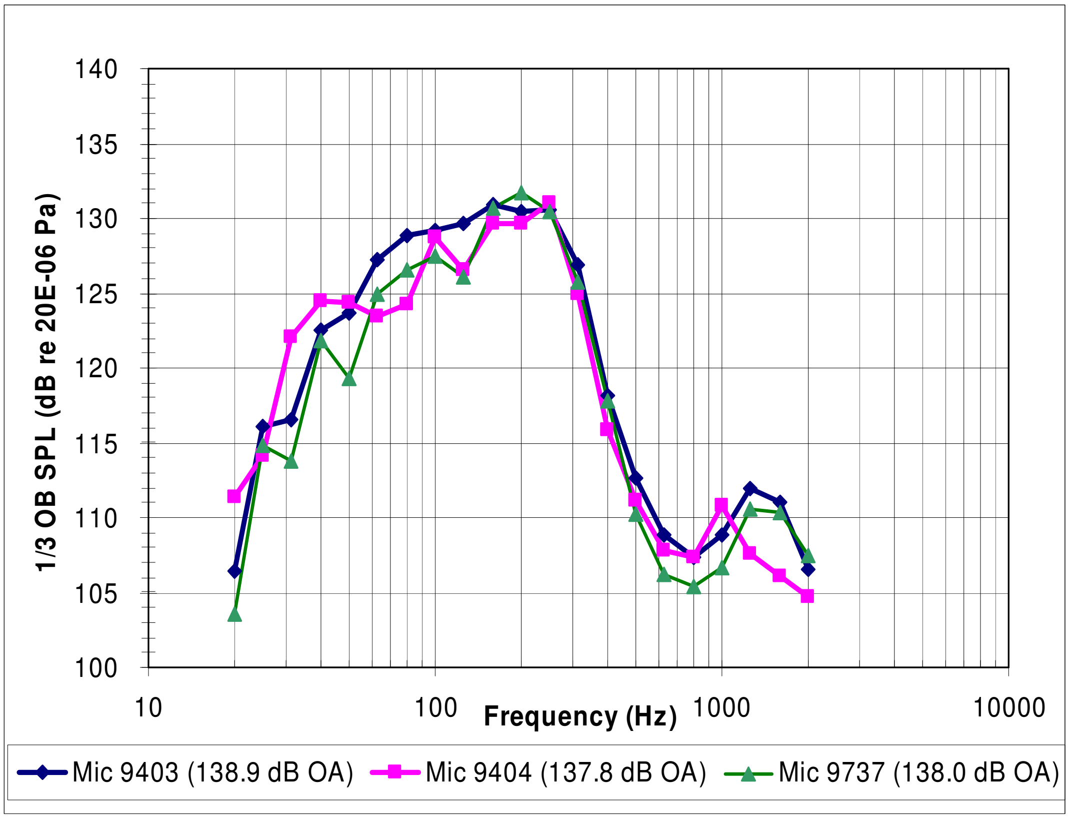


Figure A-4: **Maximax Acoustic Spectra for Titan IV Flight K-21 Internal Payload Fairing Measurements during Liftoff**

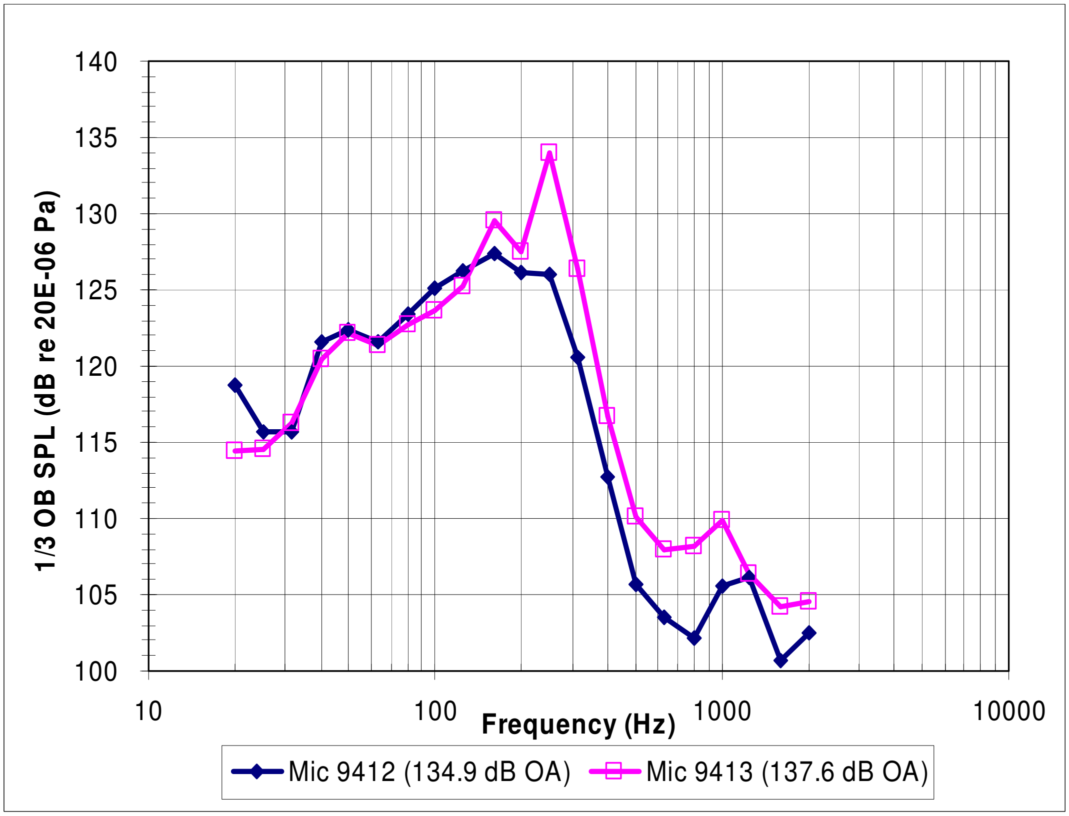


Figure A-5: **Maximax Acoustic Spectra for Titan IV Flight K-19 Internal Payload Fairing Measurements during Liftoff**

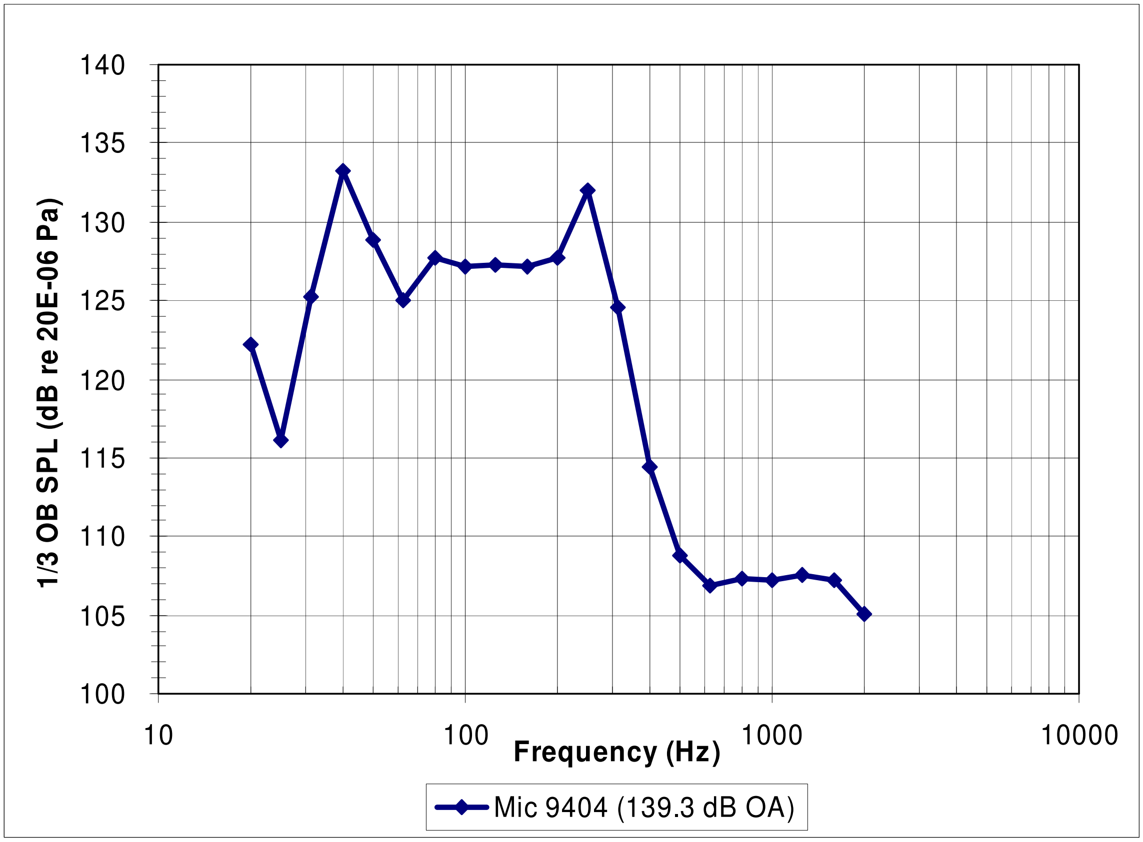


Figure A-6: **Maximax Acoustic Spectra for Titan IV Flight K-23 Internal Payload Fairing Measurements during Liftoff**

Appendix B

MATLAB Bootstrap Code

and other MATLAB Information

MATLAB BOOTSTRAP CODE

```
clear all;
close all;
%
% Program to evaluate P95/C50 and P99/C90 levels from sample data set using
% Bootstrap Method
%
% June 3, 2005
% This program modified by Bill Hughes/NASA GRC from bootstrap code provided
% by Dr. Thomas Paez/Sandia National Laboratory
%
%   Generate bootstrap replicates of the statistic of interest.
%
%   Inputs:
%   x       The raw data from which the maximum likelihood estimate and the
%           bootstrap replicates are to be generated.
%           Dimension: (ns)x(1)
%   stat    The function in which the statistic of interest (i.e. mean, std, etc.)
%           is to be computed.
%           Dimension: string
%   nr      The number of bootstrap samples (replicates) to be generated.
%           Dimension: scalar
%
%   Outputs:
%   sample_stat The maximum likelihood estimator of the parameter of interest.
%               Dimension: scalar
%
%   stat_bsrep  The bootstrap replicates of the statistic of interest.
%               Dimension: (nr)x(1)
%
%   idx         Indices of the raw data used to generate the bootstrap replicates.
%               The set of indices used to form the i(th) replicate is the i(th)
%               column of idx.
%               Dimesnion: (ns)x(nr)

% Inputs
   load SPL % reads in SPL data values from "SPL" file containing Titan IV
%            acoustic flight sound pressure level data in dB
%
% Perform loop over frequency range index (OTOB from 20 Hz to 2000 Hz)
   for fi=1:21 % frequency index (fi), where fi=1 equals 20 Hz, fi=2 equals 25 Hz,
            %....,fi=21 equals 2000 Hz, progressing in OTOB increments
      x=SPL(fi,2:18); % assign SPL data values from file; columns 2-18 correspond
                  % to the 17 Titan IV flight microphone measurements at each
                  % OTOB fi value; note column 1 in SPL file is frequency (Hz)
            % example of x for fi=12 (250 Hz) x= [129.8, 124.6, 128.2,
                  % 128.9, 123.5, 125.0, 128.6, 122.6, 125.0, 126.0, 126.5,
                  % 130.6, 131.0, 130.5, 126.0, 134.0, 132.0] consisting of
                  % 17 Titan IV flight data P/L mics @ 250 Hz

%
```

```
% Evaluate the maximum likelihood estimator (for the statistics of interest)
% from the sample population (raw data set)
      sample_mean=mean(x) % 1st statistic of interest - mean of sample
      sample_std=std(x)   % 2nd statistic of interest - standard deviation of sample
%
% Set number of bootstrap samples (nr)
      nr=1000; % number of bootstrap samples (replicates)
%
% Check for correct data inputs
      [ndum,mdum] = size(x); % checks for size of matrix of input data
      ns = max(ndum,mdum); % checks for largest dimension of input data
%
%      Logic checks for proper matrix size of raw data
         if( min (ndum,mdum)~=1 )
            fprintf('ERROR - This program is designed for univariate data only. \n');
         return;
         end % end of check loop
%
         if( ns<3 )
            fprintf('ERROR - A sample population of three or more data points are required. \n');
         return;
         end % end of check loop
%
% Set up loop to perform Bootstrap calculations
      idx = zeros(ns,nr); % Bootstrap replicate index (sample data size, # of bootstrap replicates)
%
% Create plot for each frequency
      figure
         for i=1:nr % perform loop for # bootstrap samples (replicates)
%
% Form the random indices used to select the bootstrap samples.
         idx(:,i) = floor(ns*rand(ns,1))+1;
%
% Form the bootstrap replicates for the statistics of interest
         mean_bsrep(i) = mean(x(idx(:,i))); % mean of bootstrap replicate i
         std_bsrep(i) = std(x(idx(:,i))); % std dev of bootstrap replicate i
%
%   Plot scatter graph of bootstrap replicate pairs (mean and std for each ith replicate)
         hold on;
         plot(mean_bsrep(i),std_bsrep(i),'k:o');% plots bootstrap replicate
                                        % pairs (mean and std for ith replicate)
         freq=SPL(fi,1); % for identification of frequency on plots
         title(['Bootstrap Replicate Pairs at Frequency = ',num2str(freq),' Hz ; # Bootstrap
          Replicates = ',num2str(nr),])%
         xlabel('Mean of Bootstrap Replicate')%
         ylabel('Standard Deviation of Bootstrap Replicate')%
%
```

```
%Probability Calculations
% P95 Calculations
%   For each bootstrap replicate pair of mean and std, calculate the value
%   corresponding to a normal probability of P=0.95
%
%         %Use this standardize normal equation only IF data is normally distributed
%         %P95(fi,i)=mean_bsrep(i)+((2^0.5)*std_bsrep(i)*erfinv((2*0.95)-1))
%
%   For each bootstrap replicate pair of mean and std, calculate the value
%   corresponding to a normal probability of P=0.95 using the actual
%   distribution from the SPL normalized data
        P95_SPL=1.786115; % P95 value from CDF of SPL data set
        P95(fi,i)=mean_bsrep(i) + (P95_SPL*std_bsrep(i)); % P95 bootstrap calculation
%
% P99 Calculations
%   For each bootstrap replicate pair of mean and std, calculate the value
%   corresponding to a normal probability of P=0.99
%         %Use this standardize normal equation only IF data is normally distributed
%         %P99(fi,i)=mean_bsrep(i) + ((2^0.5)*std_bsrep(i)*erfinv ((2*0.99)-1));
%
%   For each bootstrap replicate pair of mean and std, calculate the value
%   corresponding to a normal probability of P=0.99 using the actual
%   distribution of the SPL normalized data
        P99_SPL=2.481001; % P99 value from CDF of SPL data set
        P99(fi,i)=mean_bsrep(i) + (P99_SPL*std_bsrep(i)); % P99 bootstrap calculations
%
        end % end of bootstrap replicate loop
%
% For Display and Information purposes
%   Calculates the mean of all the bootstrap replicates.
      BS_mean(fi)=sum(mean_bsrep)/nr; % mean of all nr bootstrap replicate means
      BS_std(fi)=sum(std_bsrep)/nr; % mean of all nr bootsrtp replicate std
%
%   Builds matrix of bootstrap replicate mean and std
      bsrep_mean(fi,:)=mean_bsrep; % matrix of nr individual bootstrap replicate means
      bsrep_std(fi,:)=std_bsrep; % matrix of nr individual bootstrap replicate std
%
   end % end of frequency index loop
%
%   List the mean of all nr bootstrap replicates stats
      BS_mean % mean of all nr bootstrap replicate means
      BS_std % mean of all nr bootstrap replicate std
%
%   Lists the matrix of the means of each stat of interest over all bootstrap replicates
      bsrep_mean;
      bsrep_std;
%
```

```
% Confidence Limits Assessment
%  Sort Bootstrap Probabilities and Find Confidence Interval
%   P95/C50 calculation
       sortP95=sort(P95,2); % sorts bootstrap replicates of P95 values
       c50=nr*0.50; % use for 50% confidence interval
       P95C50=sortP95(:,c50)% calculates bootstrap's P95/C50 level at each frequency
%
%   P99/C90 calculation
       sortP99=sort(P99,2); % sorts bootstrap replicates of P99 values
       c90=nr*0.90; % use for 90% confidence interval
       P99C90=sortP99(:,c90)% calculates bootstrap's P99/C90 level at each frequency
%
% end of bootstrap code
```

This is list of MATLAB variables and their size used by the Bootstrap Code

```
>> whos

  Name            Size              Bytes  Class

  BS_mean         1x21                168  double array
  BS_std          1x21                168  double array
  P95            21x1000           168000  double array
  P95C50         21x1                 168  double array
  P95_SPL         1x1                   8  double array
  P99            21x1000           168000  double array
  P99C90         21x1                 168  double array
  P99_SPL         1x1                   8  double array
  SPL            21x18               3024  double array
  ans            21x1000           168000  double array
  bsrep_mean     21x1000           168000  double array
  bsrep_std      21x1000           168000  double array
  c50             1x1                   8  double array
  c90             1x1                   8  double array
  fi              1x1                   8  double array
  freq            1x1                   8  double array
  i               1x1                   8  double array
  idx            17x1000           136000  double array
  mdum            1x1                   8  double array
  mean_bsrep      1x1000             8000  double array
  ndum            1x1                   8  double array
  nr              1x1                   8  double array
  ns              1x1                   8  double array
  sample_me       1x1                   8  double array
  sample_std      1x1                   8  double array
  sortP95        21x1000           168000  double array
  sortP99        21x1000           168000  double array
  std_bsrep       1x1000             8000  double array
  x               1x17                136  double array
```

This is the SPL input file which contains the Titan IV acoustic SPL (dB) database Column 1 is frequency; Columns 2-18 is SPL data for the 17 microphones

```
>> SPL
SPL =  1.0e+003 *
```

Columns 1 through 10

0.0200	0.1062	0.1117	0.1037	0.1091	0.1074	0.1081	0.1094	0.1063	0.1075
0.0250	0.1120	0.1097	0.1112	0.1135	0.1156	0.1173	0.1142	0.1186	0.1080
0.0315	0.1218	0.1208	0.1110	0.1155	0.1177	0.1175	0.1213	0.1197	0.1150
0.0400	0.1180	0.1187	0.1172	0.1166	0.1176	0.1165	0.1132	0.1154	0.1200
0.0500	0.1175	0.1190	0.1183	0.1175	0.1188	0.1205	0.1164	0.1184	0.1190
0.0630	0.1153	0.1194	0.1231	0.1195	0.1183	0.1167	0.1163	0.1159	0.1235
0.0800	0.1156	0.1186	0.1240	0.1212	0.1215	0.1224	0.1222	0.1227	0.1245
0.1000	0.1193	0.1223	0.1255	0.1212	0.1206	0.1222	0.1217	0.1231	0.1245
0.1250	0.1222	0.1228	0.1253	0.1221	0.1238	0.1209	0.1223	0.1220	0.1260
0.1600	0.1195	0.1206	0.1273	0.1281	0.1244	0.1200	0.1227	0.1215	0.1270
0.2000	0.1263	0.1216	0.1303	0.1305	0.1236	0.1223	0.1238	0.1192	0.1265
0.2500	0.1298	0.1246	0.1282	0.1289	0.1235	0.1250	0.1286	0.1226	0.1250
0.3150	0.1244	0.1261	0.1205	0.1210	0.1177	0.1220	0.1247	0.1190	0.1220
0.4000	0.1218	0.1233	0.1143	0.1147	0.1129	0.1131	0.1158	0.1114	0.1130
0.5000	0.1192	0.1206	0.1099	0.1117	0.1106	0.1098	0.1106	0.1078	0.1095
0.6300	0.1178	0.1185	0.1065	0.1087	0.1091	0.1081	0.1088	0.1083	0.1065
0.8000	0.1181	0.1174	0.1071	0.1084	0.1102	0.1096	0.1112	0.1107	0.1085
1.0000	0.1182	0.1158	0.1085	0.1108	0.1122	0.1081	0.1135	0.1091	0.1110
1.2500	0.1122	0.1117	0.1116	0.1065	0.1110	0.1074	0.1135	0.1059	0.1130
1.6000	0.1095	0.1107	0.1117	0.1073	0.1109	0.1063	0.1145	0.1068	0.1125
2.0000	0.1147	0.1132	0.1073	0.1086	0.1119	0.1072	0.1152	0.1059	0.1160

Columns 11 through 18

0.1130	0.1050	0.1064	0.1114	0.1036	0.1188	0.1144	0.1222
0.1120	0.1100	0.1161	0.1141	0.1148	0.1157	0.1145	0.1161
0.1190	0.1150	0.1165	0.1221	0.1138	0.1157	0.1162	0.1252
0.1225	0.1205	0.1225	0.1245	0.1218	0.1216	0.1204	0.1332
0.1185	0.1190	0.1237	0.1244	0.1193	0.1224	0.1222	0.1289
0.1200	0.1200	0.1272	0.1234	0.1249	0.1216	0.1214	0.1250
0.1225	0.1225	0.1289	0.1242	0.1265	0.1234	0.1227	0.1277
0.1240	0.1215	0.1292	0.1287	0.1275	0.1251	0.1236	0.1272
0.1260	0.1260	0.1297	0.1265	0.1261	0.1262	0.1252	0.1273
0.1270	0.1280	0.1309	0.1297	0.1307	0.1274	0.1295	0.1271
0.1265	0.1265	0.1305	0.1297	0.1317	0.1261	0.1275	0.1277
0.1260	0.1265	0.1306	0.1310	0.1305	0.1260	0.1340	0.1320
0.1215	0.1215	0.1269	0.1250	0.1257	0.1206	0.1264	0.1246
0.1115	0.1120	0.1182	0.1159	0.1178	0.1127	0.1167	0.1144
0.1085	0.1090	0.1126	0.1111	0.1102	0.1057	0.1101	0.1088
0.1045	0.1060	0.1089	0.1078	0.1062	0.1035	0.1079	0.1069
0.1045	0.1030	0.1074	0.1073	0.1054	0.1022	0.1082	0.1073
0.1065	0.1075	0.1089	0.1108	0.1067	0.1056	0.1099	0.1072
0.1065	0.1105	0.1119	0.1076	0.1106	0.1061	0.1064	0.1076
0.1070	0.1080	0.1110	0.1061	0.1104	0.1007	0.1042	0.1072
0.1100	0.1090	0.1065	0.1047	0.1075	0.1025	0.1046	0.1051

Output from MATLAB Bootstrap Code:
Using all OTOB frequencies, using all 17 mics, nr=1000 with PLOTS
Column value corresponds to each OTOB frequency

nr = 1000

BS_mean =

Columns 1 through 8

109.6073 113.6980 117.8515 119.9920 120.2291 120.6643 122.9567 123.9662

Columns 9 through 16

124.7288 125.9733 126.4893 127.7743 122.9040 115.2469 110.9528 108.4432

Columns 17 through 21

108.6318 109.9957 109.3750 108.5690 108.8297

BS_std =

Columns 1 through 8

4.8168 2.7633 3.4501 4.2520 2.9847 3.3787 2.9391 2.7955

Columns 9 through 16

2.2623 3.6478 3.3579 3.1149 2.6498 3.2702 3.5172 3.6952

Columns 17 through 21

4.0178 3.2318 2.6234 3.2370 3.9195

P95C50 =
118.2010
118.6173
124.0384
127.7473
125.6064
126.7598
128.2592
129.0186
128.7695
132.5052
132.5238
133.2813
127.6919
121.1647
117.4429
115.4107
115.9262
115.9044
114.1295
114.3894
116.0051

P99C90 =
126.0433
121.9283
128.6647
134.7997
130.4816
130.8244
132.3629
132.6366
131.6636
136.3097
136.4060
137.3120
130.6905
126.3905
123.4524
121.8352
122.1539
120.7177
116.9255
118.5772
120.8803

Appendix C

z-Values for Titan IV Liftoff Acoustic Database

(Tables)

Table C-1: **z-Values for Liftoff Acoustic Data from Titan IV K-1 and K-4 Flights (interior PLF microphones)**

	K-1		K-4					
Type	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT
Station	155	155	370	207	207	104	104	104
Azimuth	90 Deg	270 Deg	350 Deg	350 Deg	180 Deg	350 Deg	90 Deg	180 Deg
	9700	**9725**	**9737**	**9738**	**9739**	**9740**	**9741**	**9742**
Frequency (Hz)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)
20.0	-0.7	0.4	-1.2	-0.1	-0.4	-0.3	-0.1	-0.7
25.0	-0.6	-1.4	-0.9	-0.1	0.6	1.2	0.2	1.7
31.5	1.1	0.8	-1.9	-0.7	0.0	-0.1	1.0	0.5
40.0	-0.4	-0.3	-0.6	-0.8	-0.5	-0.8	-1.5	-1.0
50.0	-0.9	-0.4	-0.6	-0.9	-0.4	0.1	-1.2	-0.6
63.0	-1.5	-0.4	0.7	-0.3	-0.7	-1.1	-1.2	-1.4
80.0	-2.4	-1.4	0.3	-0.6	-0.5	-0.2	-0.3	-0.1
100.0	-1.6	-0.6	0.5	-0.9	-1.2	-0.6	-0.8	-0.3
125.0	-1.1	-0.8	0.2	-1.1	-0.4	-1.6	-1.0	-1.2
160.0	-1.7	-1.4	0.4	0.6	-0.4	-1.6	-0.9	-1.2
200.0	-0.1	-1.4	1.1	1.1	-0.8	-1.2	-0.8	-2.1
250.0	0.6	-1.0	0.1	0.3	-1.3	-0.9	0.2	-1.6
315.0	0.5	1.2	-0.9	-0.7	-1.9	-0.3	0.6	-1.4
400.0	1.9	2.3	-0.3	-0.2	-0.7	-0.6	0.2	-1.1
500.0	2.2	2.6	-0.3	0.2	-0.1	-0.3	-0.1	-0.8
630.0	2.4	2.5	-0.5	0.1	0.2	-0.1	0.1	0.0
800.0	2.2	2.1	-0.4	-0.1	0.4	0.2	0.6	0.5
1000.0	2.4	1.7	-0.4	0.2	0.6	-0.6	1.0	-0.3
1250.0	1.0	0.8	0.8	-1.1	0.6	-0.7	1.5	-1.3
1600.0	0.3	0.6	0.9	-0.4	0.7	-0.7	1.8	-0.5
2000.0	1.4	1.1	-0.4	-0.1	0.8	-0.4	1.6	-0.7

Table C-2: **z-Values for Liftoff Acoustic Data from Titan IV K-10 and K-21 Flights (interior PLF microphones)**

	K-10			K-21		
Type	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT	PLF INT
Station	63 in aft CCJ	492	63 in aft CCJ	63 in aft CCJ	492	63 in aft CCJ
Azimuth	180 Deg	90 Deg	350 Deg	180 Deg	90 Deg	350 Deg
Frequency (Hz)	**9403 SPL** (dB)	**9404 SPL** (dB)	**9737 SPL** (dB)	**9403 SPL** (dB)	**9404 SPL** (dB)	**9737 SPL** (dB)
20.0	-0.4	0.7	-0.9	-0.6	0.3	-1.2
25.0	-2.0	-0.6	-1.3	0.8	0.1	0.4
31.5	-0.8	0.3	-0.8	-0.4	1.2	-1.1
40.0	0.0	0.6	0.1	0.6	1.0	0.4
50.0	-0.4	-0.5	-0.4	1.1	1.3	-0.3
63.0	0.8	-0.2	-0.2	1.9	0.8	1.2
80.0	0.5	-0.2	-0.2	1.9	0.4	1.1
100.0	0.2	0.0	-0.8	1.8	1.6	1.2
125.0	0.5	0.5	0.5	2.1	0.7	0.6
160.0	0.3	0.3	0.5	1.3	1.0	1.3
200.0	0.0	0.0	0.0	1.1	0.9	1.5
250.0	-0.9	-0.6	-0.4	0.9	1.0	0.8
315.0	-0.3	-0.5	-0.5	1.4	0.8	1.0
400.0	-0.7	-1.1	-1.0	0.9	0.2	0.7
500.0	-0.4	-0.6	-0.5	0.4	0.0	-0.2
630.0	-0.5	-1.0	-0.6	0.1	-0.2	-0.6
800.0	0.0	-1.0	-1.3	-0.3	-0.3	-0.8
1000.0	0.3	-1.0	-0.7	-0.3	0.2	-1.0
1250.0	1.3	-1.1	0.4	0.9	-0.7	0.4
1600.0	1.2	-0.4	-0.2	0.7	-0.7	0.6
2000.0	1.8	0.3	0.0	-0.6	-1.0	-0.3

Table C-3: **z-Values for Liftoff Acoustic Data from Titan IV K-19 and K-23 Flights (interior PLF microphones)**

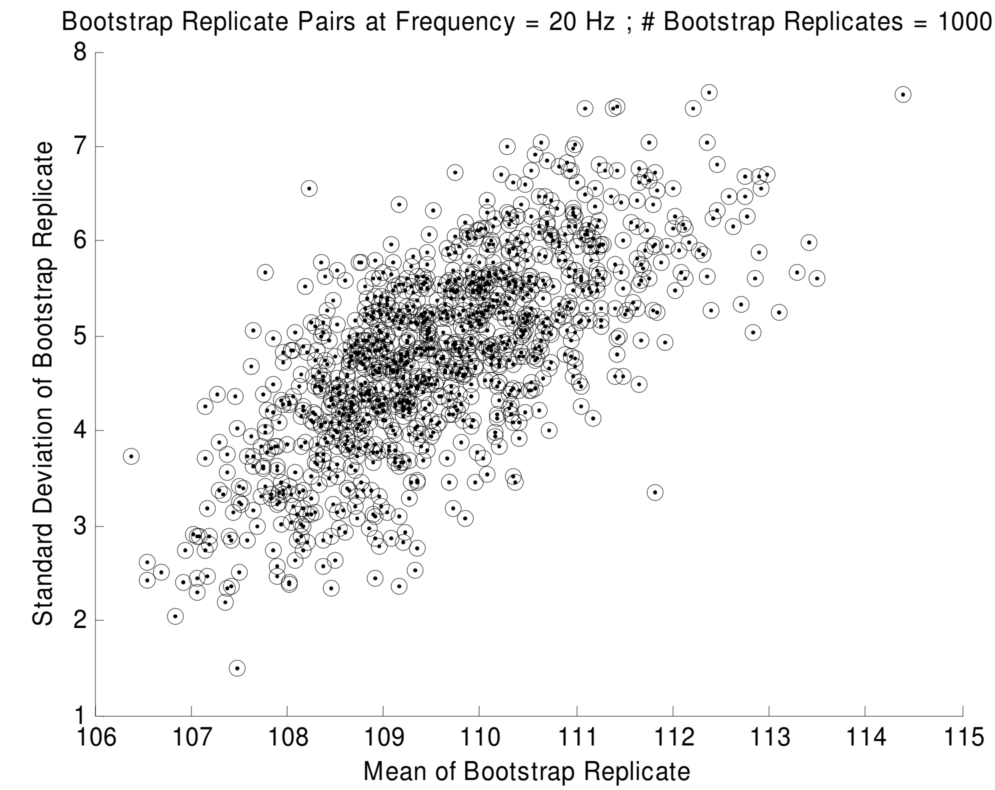
	K-19		K-23
Type	PLF INT	PLF INT	PLF INT
Station	432	432	492
Azimuth	0 Deg	90 Deg	90 Deg
	9412	**9413**	**9404**
Frequency (Hz)	**SPL** (dB)	**SPL** (dB)	**SPL** (dB)
20.0	1.8	0.9	2.4
25.0	0.7	0.3	0.8
31.5	-0.6	-0.5	2.0
40.0	0.4	0.1	2.9
50.0	0.7	0.6	2.7
63.0	0.3	0.2	1.2
80.0	0.1	-0.1	1.5
100.0	0.4	-0.1	1.1
125.0	0.6	0.2	1.1
160.0	0.4	0.9	0.3
200.0	-0.1	0.3	0.3
250.0	-0.6	1.9	1.3
315.0	-0.8	1.3	0.6
400.0	-0.7	0.4	-0.3
500.0	-1.4	-0.2	-0.6
630.0	-1.3	-0.1	-0.4
800.0	-1.5	-0.1	-0.3
1000.0	-1.3	0.0	-0.8
1250.0	-1.2	-1.1	-0.7
1600.0	-2.3	-1.3	-0.4
2000.0	-1.5	-1.0	-0.9

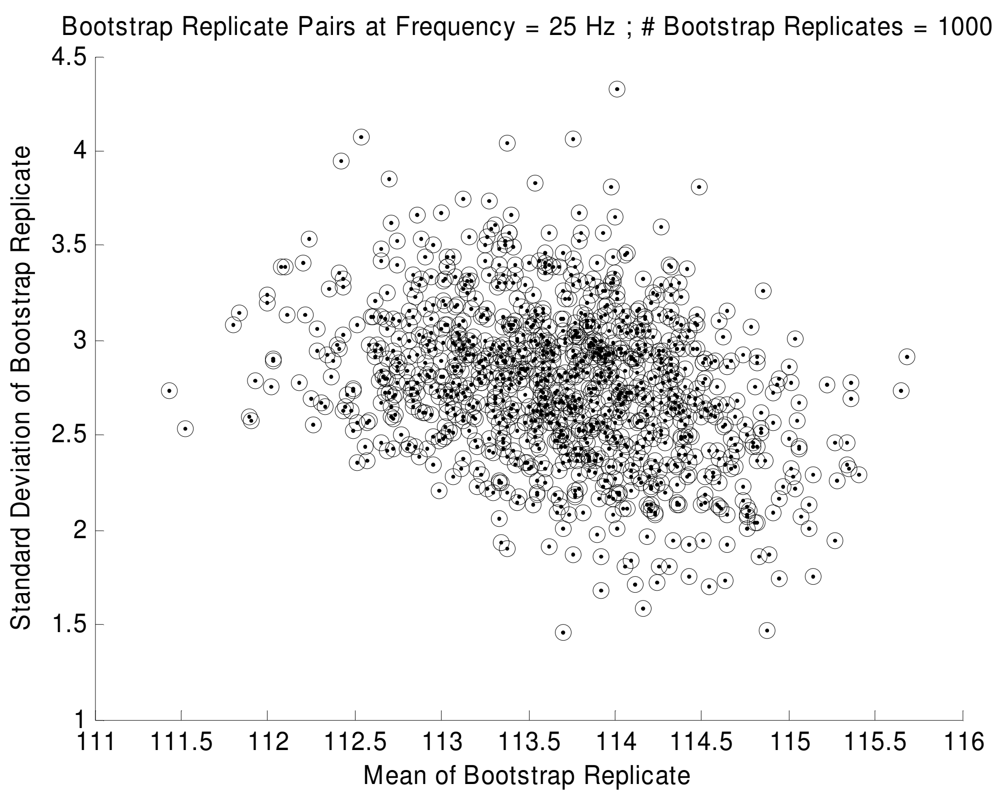
Appendix D

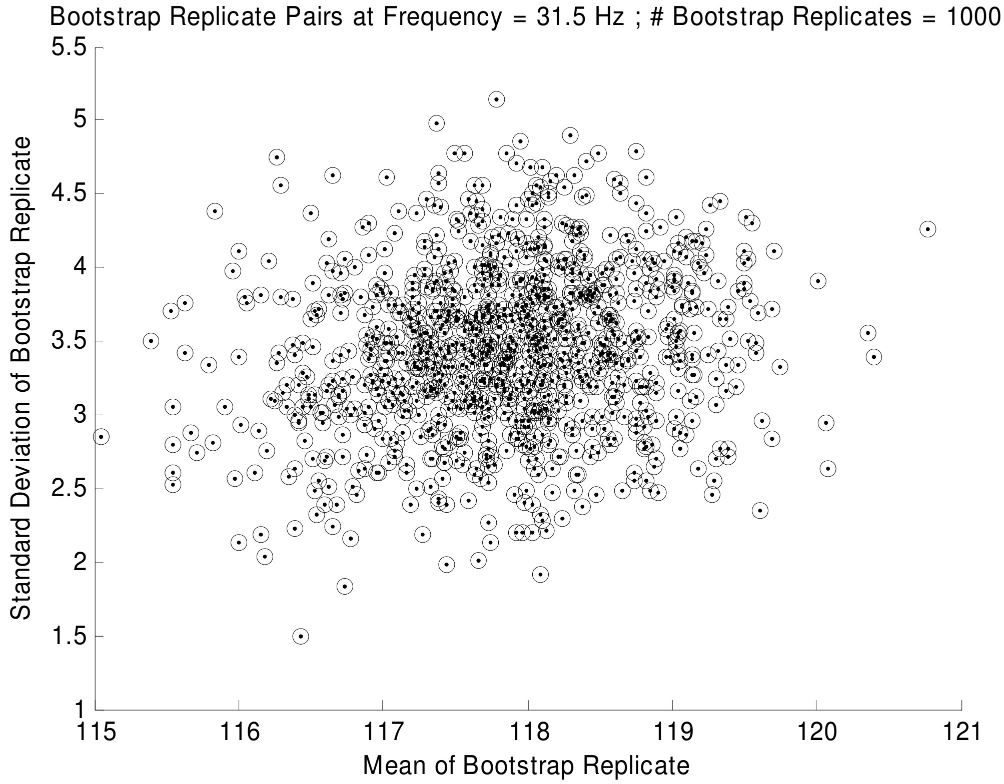
Bootstrap Results:

Plots of Replicate Pairs of Means and Standard Deviations

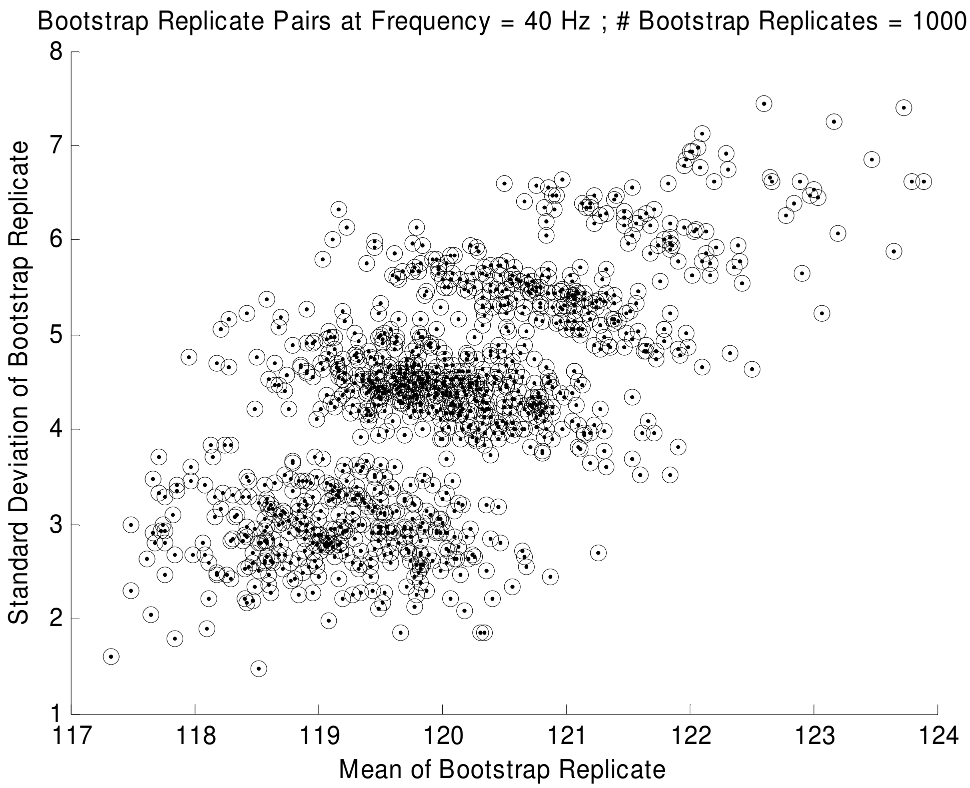
For nr= 1000 Replicates


Bootstrap Replicate Pairs at Frequency = 20 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
8
7
6
5
4
3
2
1
106
107
108
109
110
111
112
113
114
115

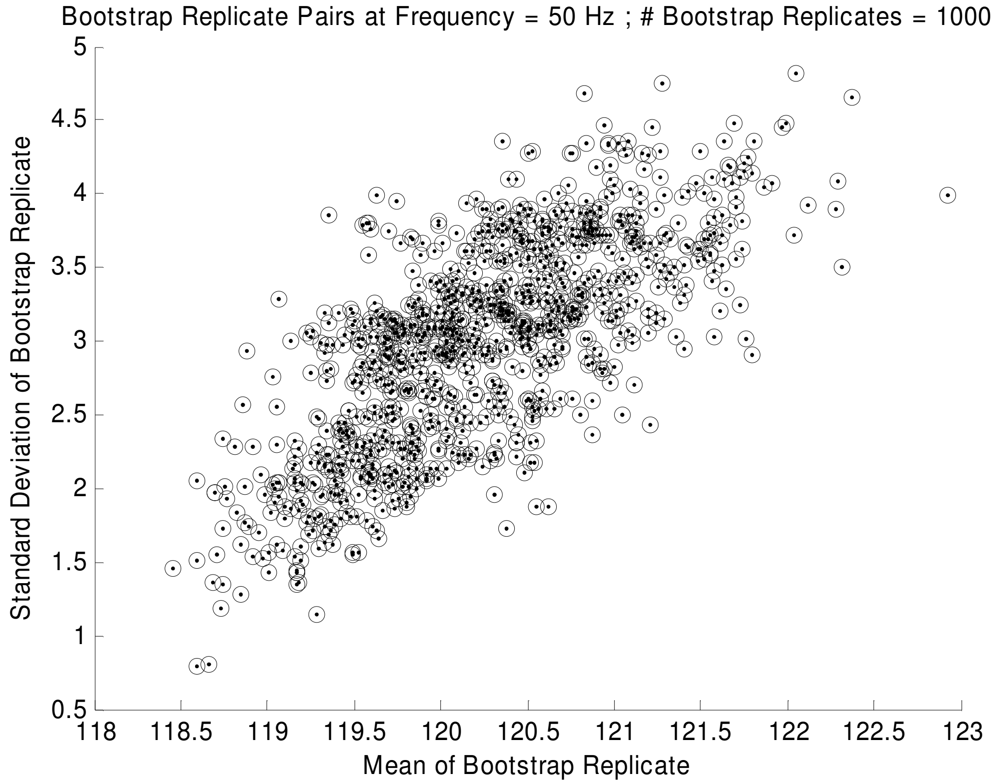

Bootstrap Replicate Pairs at Frequency = 25 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
4.5
4
3.5
3
2.5
2
1.5
1
111
111.5
112
112.5
113
113.5
114
114.5
115
115.5
116

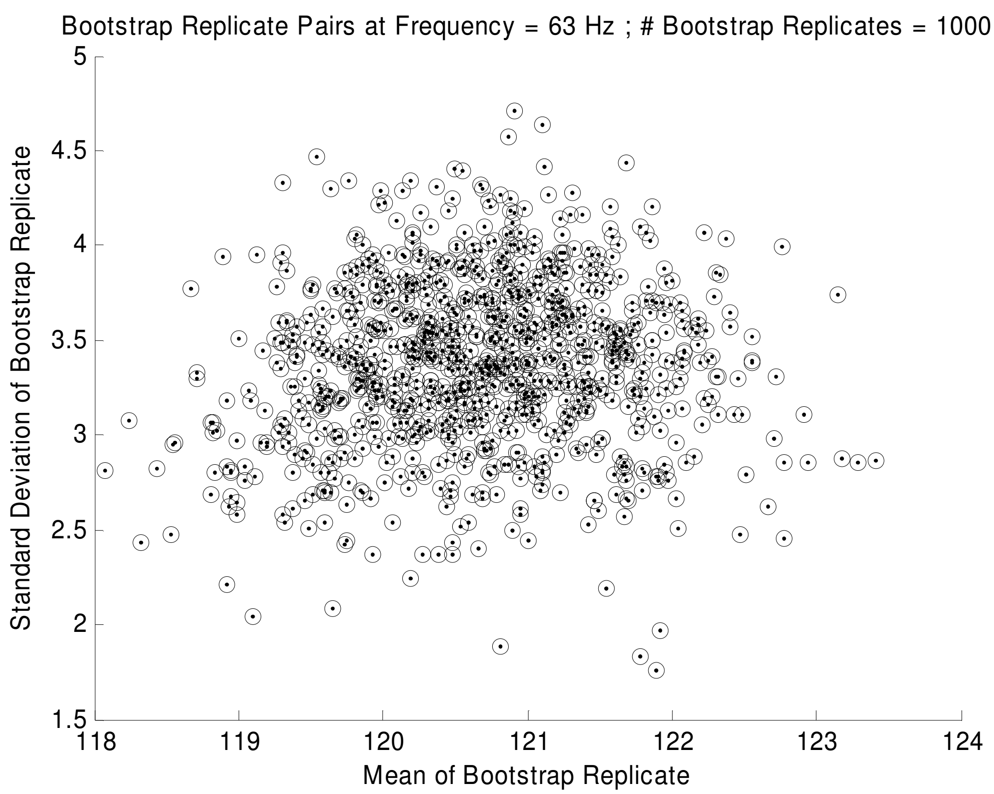


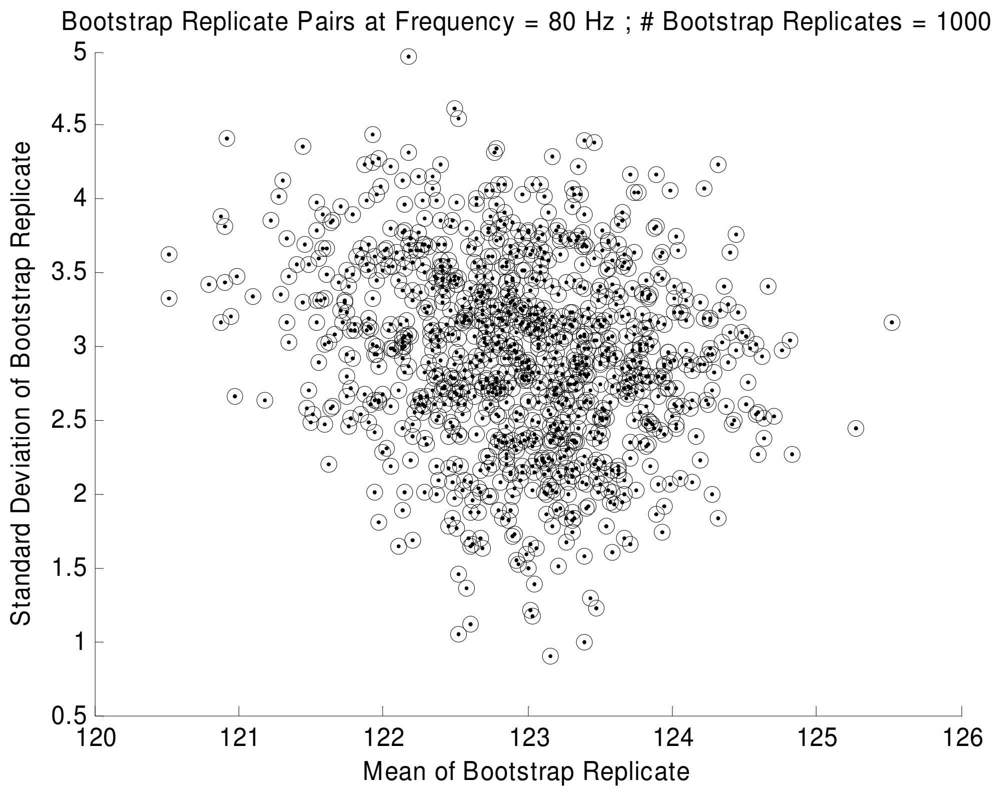
Bootstrap Replicate Pairs at Frequency = 31.5 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
115
116
117
118
119
120
121

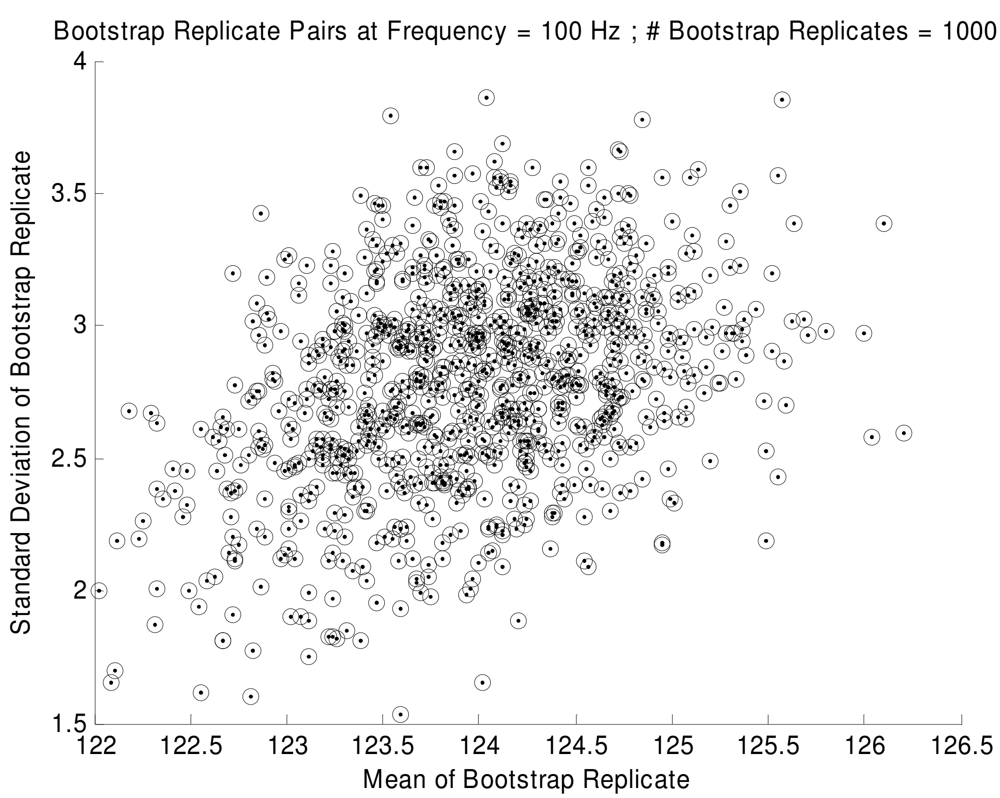


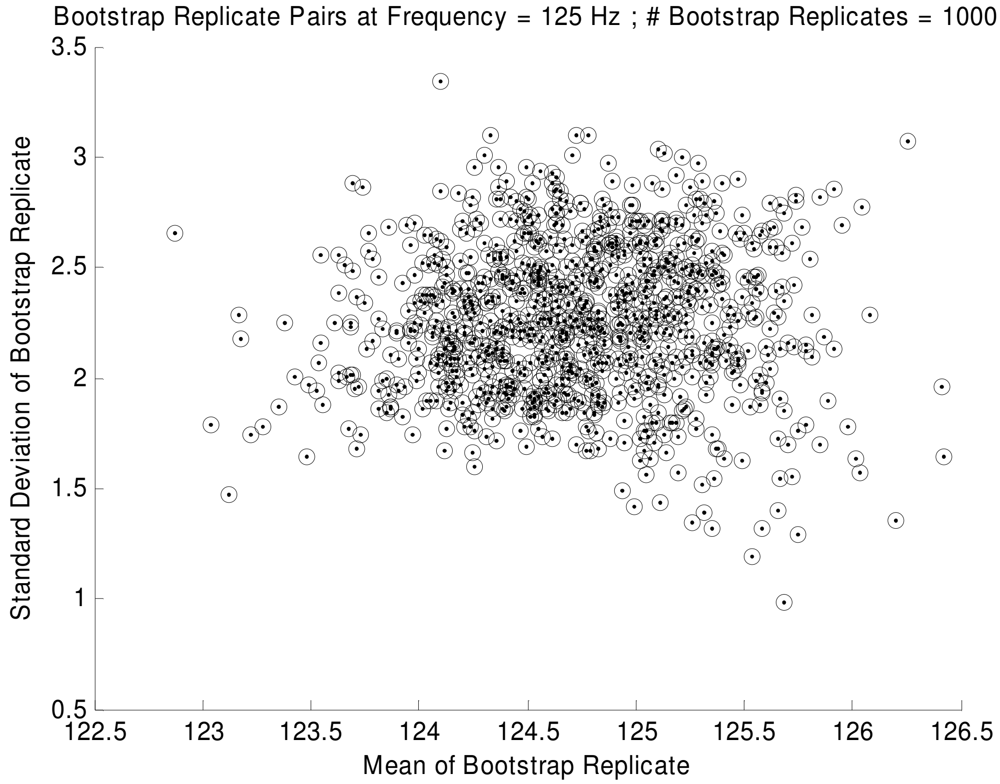
Bootstrap Replicate Pairs at Frequency = 40 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
8
7
6
5
4
3
2
1
117
118
119
120
121
122
123
124

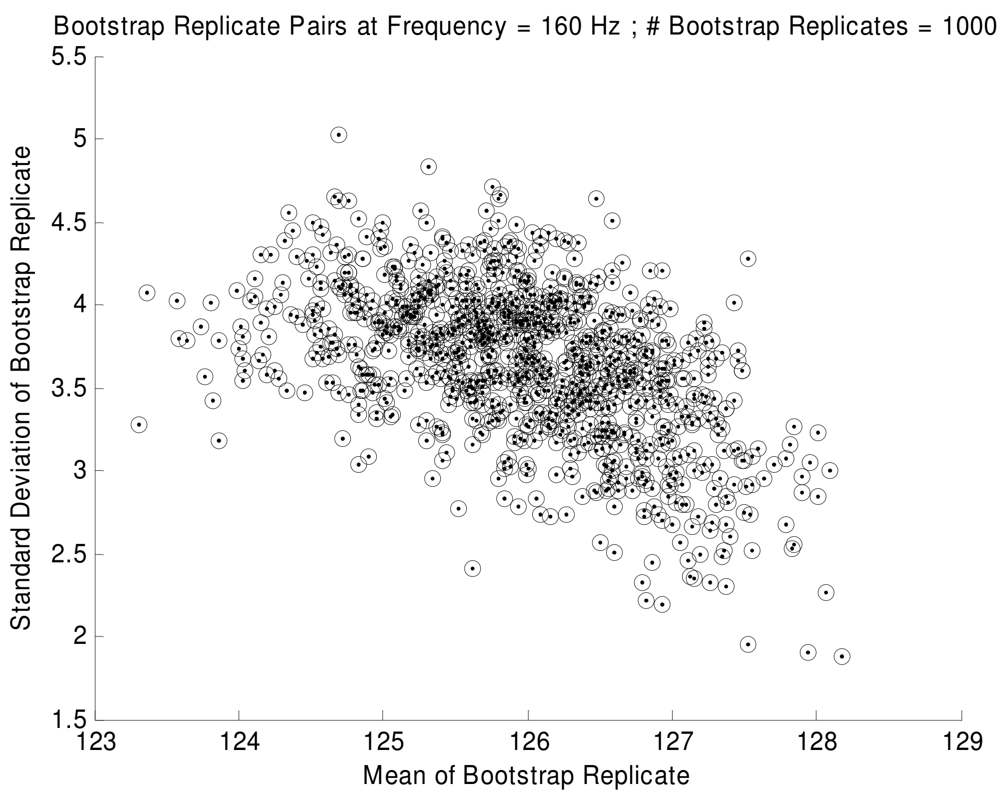

Bootstrap Replicate Pairs at Frequency = 50 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
118
118.5
119
119.5
120
120.5
121
121.5
122
122.5
123

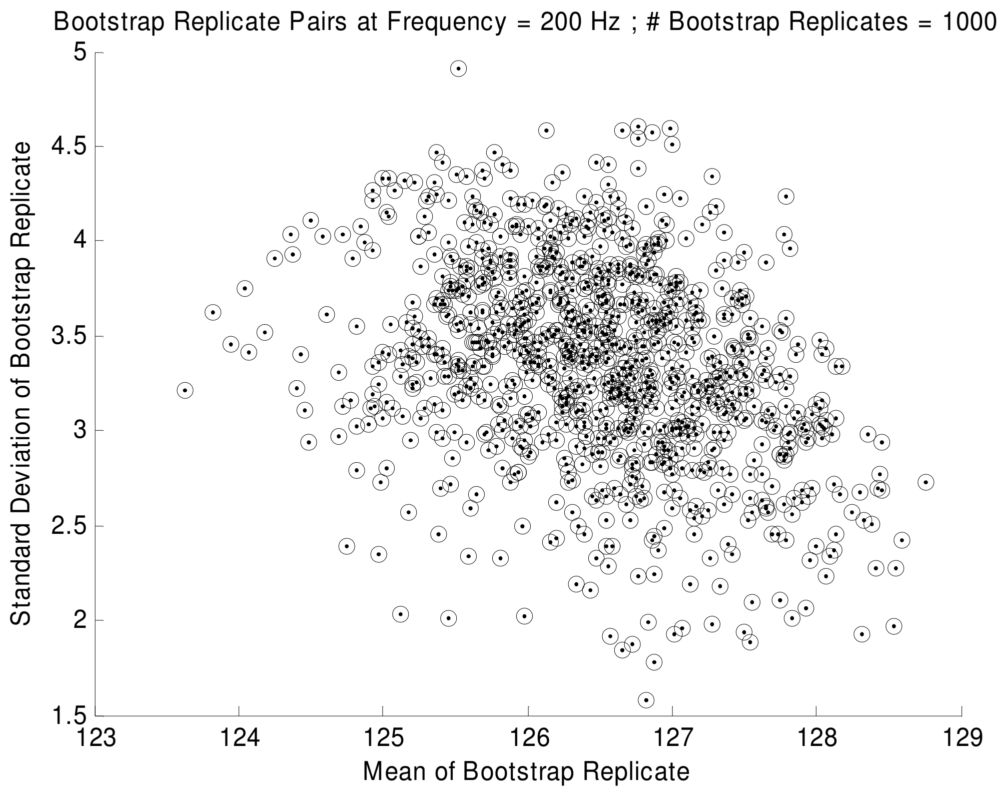

Bootstrap Replicate Pairs at Frequency = 63 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
1.5
2
2.5
3
3.5
4
4.5
5
118
119
120
121
122
123
124

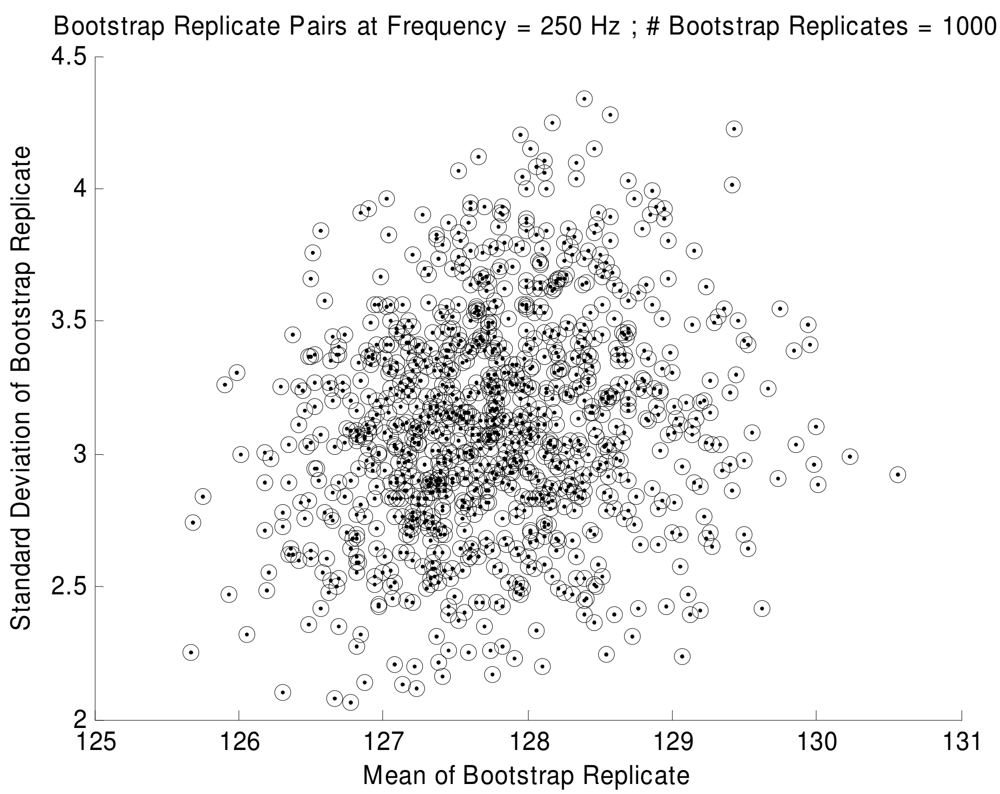

Bootstrap Replicate Pairs at Frequency = 80 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
120
121
122
123
124
125
126

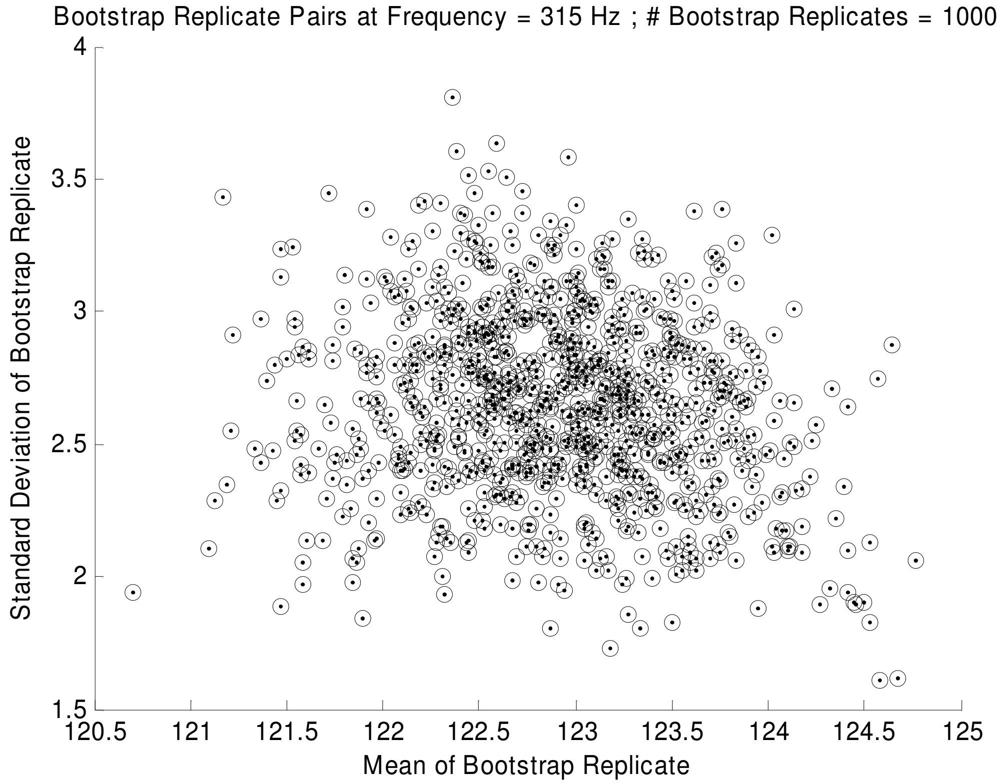

Bootstrap Replicate Pairs at Frequency = 100 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
4
3.5
3
2.5
2
1.5
122
122.5
123
123.5
124
124.5
125
125.5
126
126.5

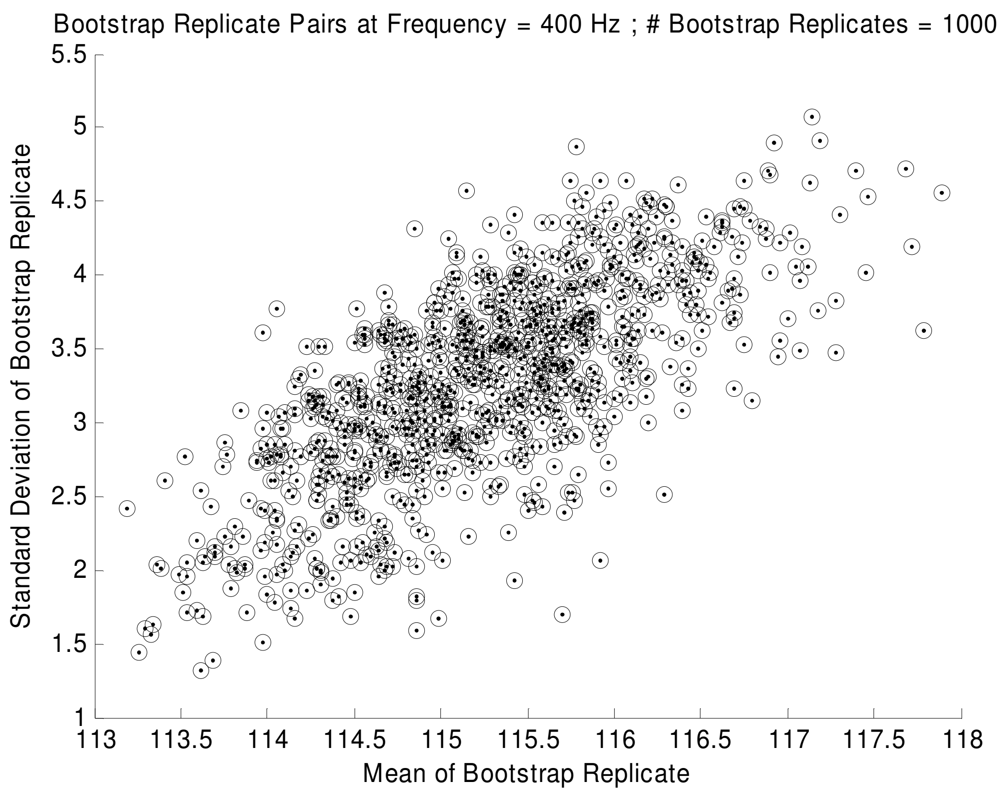

Bootstrap Replicate Pairs at Frequency = 125 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
3.5
3
2.5
2
1.5
1
0.5
122.5
123
123.5
124
124.5
125
125.5
126
126.5

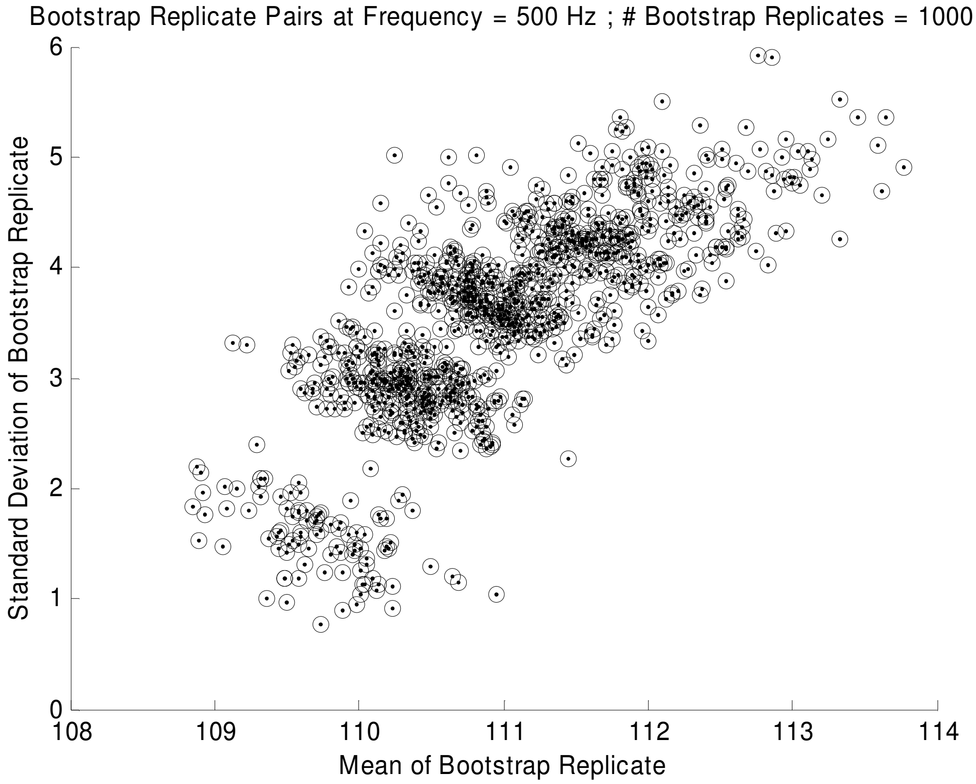

Bootstrap Replicate Pairs at Frequency = 160 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
5.5
5
4.5
4
3.5
3
2.5
2
1.5
123
124
125
126
127
128
129

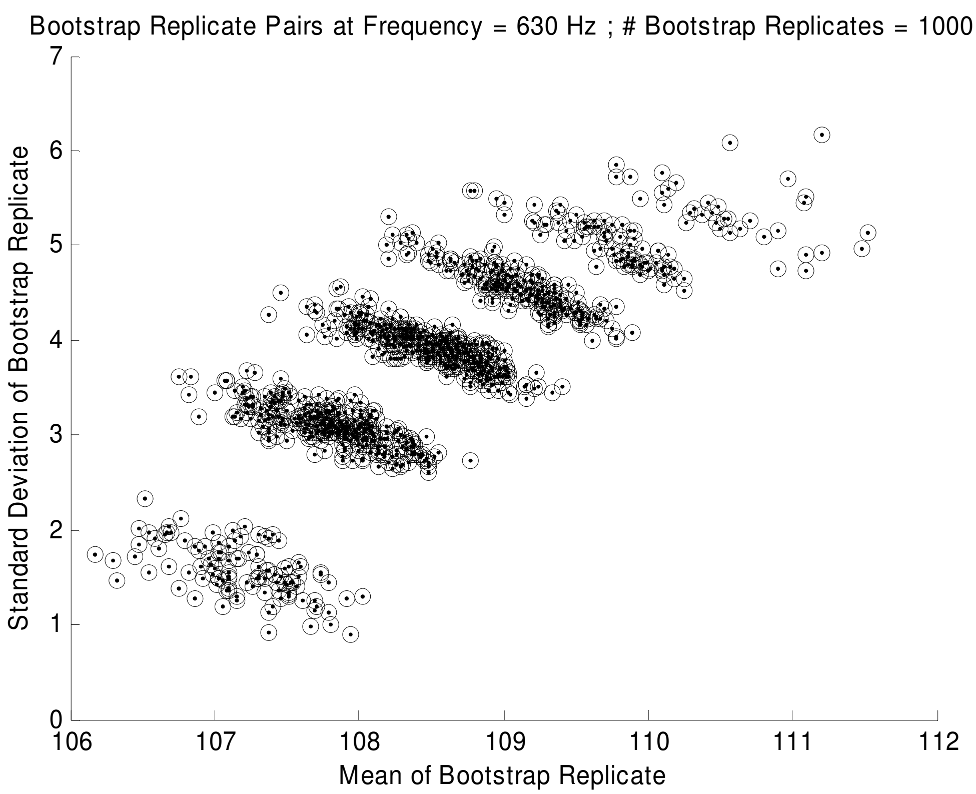

Bootstrap Replicate Pairs at Frequency = 200 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
5
4.5
4
3.5
3
2.5
2
1.5
123
124
125
126
127
128
129

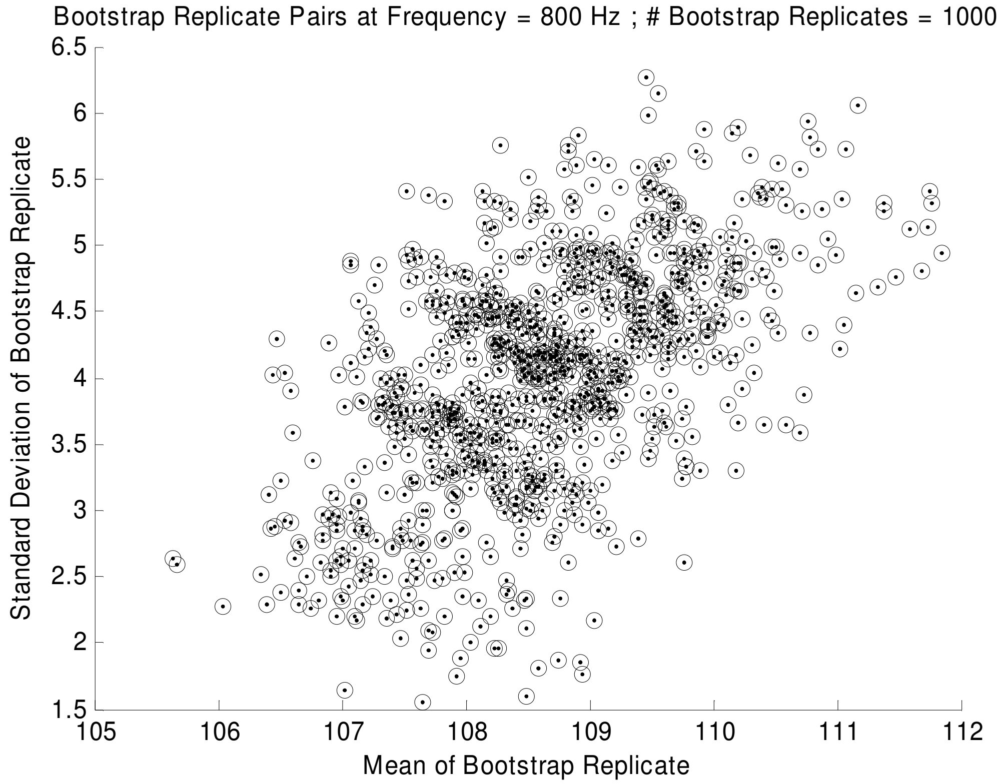

Bootstrap Replicate Pairs at Frequency = 250 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
4.5
4
3.5
3
2.5
2
125
126
127
128
129
130
131

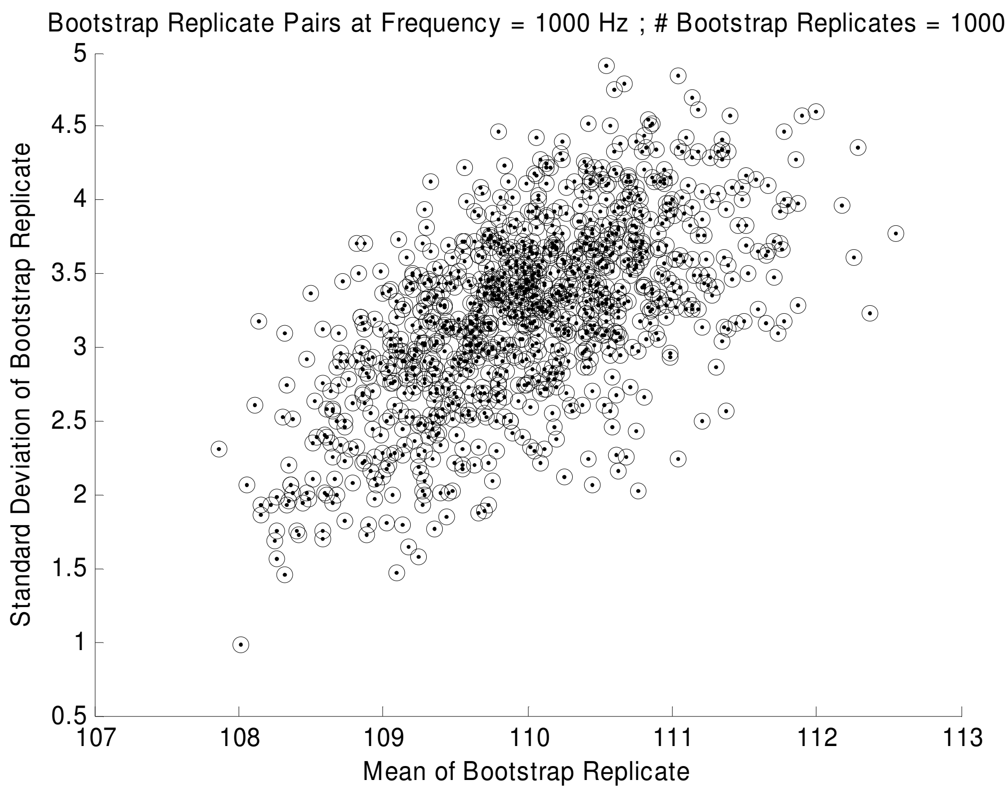

Bootstrap Replicate Pairs at Frequency = 315 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
4
3.5
3
2.5
2
1.5
120.5
121
121.5
122
122.5
123
123.5
124
124.5
125


Bootstrap Replicate Pairs at Frequency = 400 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
113
113.5
114
114.5
115
115.5
116
116.5
117
117.5
118

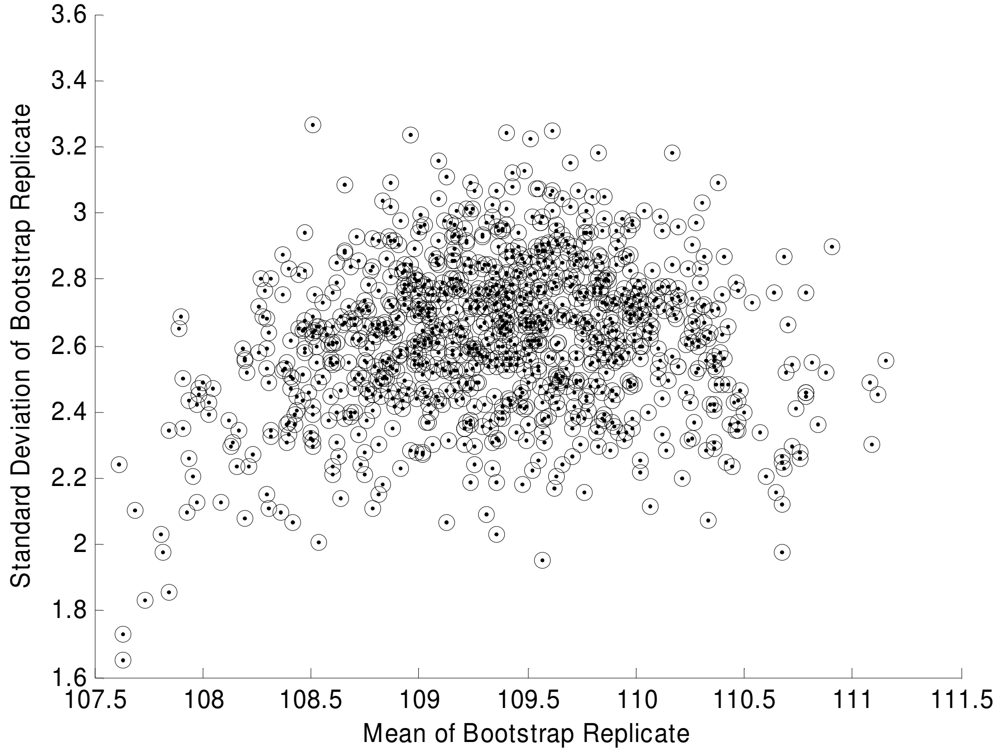

Bootstrap Replicate Pairs at Frequency = 500 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
0
1
2
3
4
5
6
108
109
110
111
112
113
114


Bootstrap Replicate Pairs at Frequency = 630 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
0
1
2
3
4
5
6
7
106
107
108
109
110
111
112

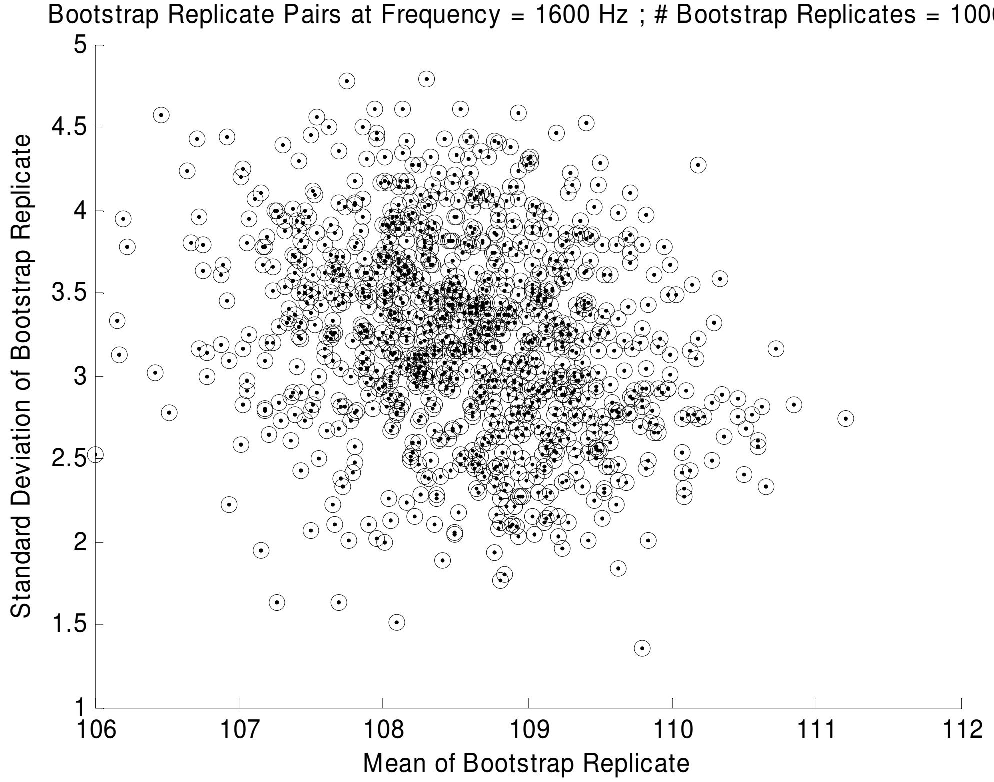

Bootstrap Replicate Pairs at Frequency = 800 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
105
106
107
108
109
110
111
112

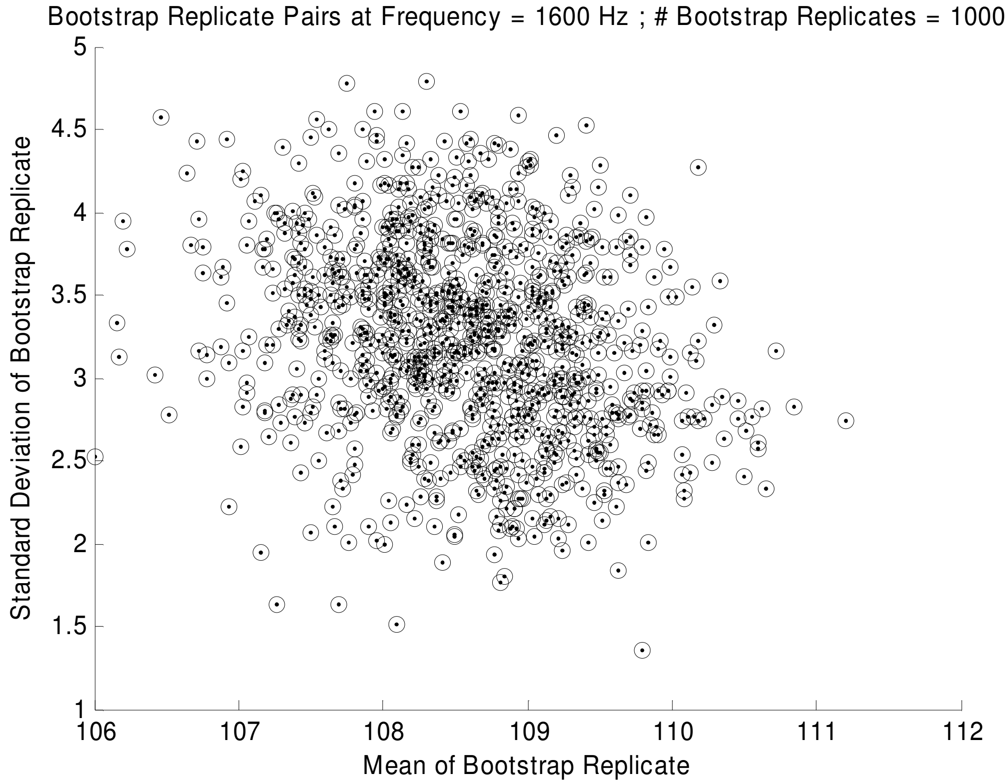

Bootstrap Replicate Pairs at Frequency = 1000 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
107
108
109
110
111
112
113

Bootstrap Replicate Pairs at Frequency = 1250 Hz ; # Bootstrap Replicates = 1000



Bootstrap Replicate Pairs at Frequency = 1600 Hz ; # Bootstrap Replicates = 1000




Bootstrap Replicate Pairs at Frequency = 1600 Hz ; # Bootstrap Replicates = 1000
Standard Deviation of Bootstrap Replicate
Mean of Bootstrap Replicate
5
4.5
4
3.5
3
2.5
2
1.5
1
106
107
108
109
110
111
112

Appendix E

Study of the Affect of the Number of Bootstrap Samples (nr)

on Bootstrap Results (Tables)

Table E-1: **Mean of Bootstrap Replicate Means as a function of Number of Samples (nr)**

Frequency (Hz)	Sample Mean	Bootstrap nr=50	Bootstrap nr=500	Bootstrap nr=1000	Bootstrap nr=5000	Bootstrap nr=5000
20.0	109.7	109.6	109.7	109.6	109.7	109.7
25.0	113.7	113.9	113.8	113.7	113.7	113.7
31.5	117.9	118.1	117.8	117.9	117.9	117.9
40.0	120.0	120.4	119.9	120.0	120.0	120.0
50.0	120.2	120.1	120.2	120.2	120.2	120.2
63.0	120.7	120.7	120.7	120.7	120.7	120.7
80.0	123.0	123.0	123.0	123.0	123.0	123.0
100.0	124.0	124.0	123.9	124.0	123.9	123.9
125.0	124.7	124.7	124.8	124.7	124.7	124.7
160.0	126.0	126.0	126.0	126.0	126.0	126.0
200.0	126.5	126.7	126.5	126.5	126.5	126.5
250.0	127.8	127.8	127.9	127.8	127.8	127.8
315.0	122.9	122.9	122.9	122.9	122.9	122.9
400.0	115.3	115.1	115.2	115.2	115.3	115.3
500.0	110.9	111.0	111.0	111.0	110.9	110.9
630.0	108.5	108.2	108.5	108.4	108.5	108.5
800.0	108.6	108.7	108.6	108.6	108.6	108.6
1000.0	110.0	110.1	110.0	110.0	110.0	110.0
1250.0	109.4	109.4	109.4	109.4	109.4	109.4
1600.0	108.5	108.6	108.5	108.6	108.5	108.5
2000.0	108.8	108.7	108.8	108.8	108.8	108.8

Table E-2: **Mean of Bootstrap Replicate <u>Standard Deviation</u> as a function of Number of Samples (nr)**

Frequency (Hz)	**Sample Std Dev**	**Bootstrap nr=50**	**Bootstrap nr=500**	**Bootstrap nr=1000**	**Bootstrap nr=5000**	**Bootstrap nr=5000**
20.0	5.1	4.8	5.0	4.8	4.9	4.9
25.0	2.9	2.7	2.8	2.8	2.8	2.8
31.5	3.6	3.6	3.4	3.5	3.4	3.4
40.0	4.5	4.5	4.1	4.3	4.2	4.2
50.0	3.2	3.0	2.9	3.0	3.0	3.0
63.0	3.5	3.3	3.4	3.4	3.4	3.4
80.0	3.1	3.1	3.0	2.9	3.0	3.0
100.0	2.9	2.8	2.8	2.8	2.8	2.8
125.0	2.4	2.3	2.3	2.3	2.3	2.3
160.0	3.8	3.7	3.7	3.6	3.6	3.6
200.0	3.5	3.4	3.4	3.4	3.4	3.4
250.0	3.2	3.1	3.1	3.1	3.1	3.1
315.0	2.8	2.8	2.6	2.6	2.7	2.7
400.0	3.4	3.1	3.2	3.3	3.3	3.3
500.0	3.7	3.4	3.5	3.5	3.5	3.5
630.0	4.0	3.4	3.7	3.7	3.7	3.7
800.0	4.3	4.2	4.0	4.0	4.0	4.0
1000.0	3.4	3.3	3.2	3.2	3.2	3.2
1250.0	2.7	2.7	2.6	2.6	2.6	2.6
1600.0	3.4	3.3	3.2	3.2	3.2	3.2
2000.0	4.1	3.9	3.9	3.9	3.9	3.9

Table E-3: **Bootstrap <u>P95/C50</u> Value**
as a function of Number of Samples (nr)

Frequency (Hz)	**NTL P95/C50**	**Bootstrap nr=50**	**Bootstrap nr=500**	**Bootstrap nr=1000**	**Bootstrap nr=5000**	**Bootstrap nr=5000**
20.0	118.3	118.1	118.8	118.2	118.5	118.4
25.0	118.6	118.5	118.7	118.6	118.7	118.7
31.5	123.9	124.6	123.9	124.0	124.1	124.1
40.0	127.6	128.5	127.5	127.7	127.8	127.7
50.0	125.5	125.5	125.5	125.6	125.6	125.6
63.0	126.6	126.6	126.8	126.8	126.8	126.8
80.0	128.2	128.3	128.4	128.3	128.3	128.3
100.0	128.8	129.2	128.9	129.0	129.0	129.0
125.0	128.7	128.9	128.8	128.8	128.8	128.8
160.0	132.3	132.6	132.6	132.5	132.5	132.5
200.0	132.4	132.6	132.5	132.5	132.5	132.5
250.0	133.2	133.3	133.5	133.3	133.4	133.4
315.0	127.5	127.7	127.7	127.7	127.7	127.7
400.0	121.0	120.8	121.0	121.2	121.2	121.2
500.0	117.2	117.3	117.5	117.4	117.4	117.4
630.0	115.1	113.6	115.5	115.4	115.4	115.4
800.0	115.7	116.3	115.9	115.9	116.0	116.0
1000.0	115.7	115.7	115.8	115.9	115.9	115.8
1250.0	114.0	114.4	114.2	114.1	114.2	114.2
1600.0	114.2	114.4	114.2	114.4	114.2	114.3
2000.0	115.7	115.7	115.9	116.0	115.9	115.9

Table E-4: **Bootstrap P99/C90 Value as a function of Number of Samples (nr)**

Frequency (Hz)	NTL P99/C90	Bootstrap nr=50	Bootstrap nr=500	Bootstrap nr=1000	Bootstrap nr=5000	Bootstrap nr=5000
20.0	125.8	126.2	126.1	126.0	126.1	126.1
25.0	122.8	121.7	121.9	121.9	121.9	121.9
31.5	129.2	129.5	128.6	128.7	128.6	128.6
40.0	134.1	136.4	134.6	134.8	134.8	134.9
50.0	130.2	130.9	130.6	130.5	130.7	130.6
63.0	131.7	130.6	131.0	130.8	130.9	130.9
80.0	132.8	132.7	132.3	132.4	132.4	132.4
100.0	133.1	132.8	132.3	132.6	132.6	132.6
125.0	132.2	131.7	131.7	131.7	131.7	131.7
160.0	137.8	136.3	136.4	136.3	136.3	136.3
200.0	137.5	136.5	136.3	136.4	136.4	136.4
250.0	137.9	136.6	137.3	137.3	137.3	137.2
315.0	131.6	131.0	130.7	130.7	130.7	130.7
400.0	126.0	125.5	126.1	126.4	126.2	126.2
500.0	122.6	123.2	123.3	123.5	123.5	123.5
630.0	120.9	121.6	122.0	121.8	122.0	122.0
800.0	122.0	121.7	121.9	122.2	122.2	122.1
1000.0	120.7	120.5	120.8	120.7	120.8	120.8
1250.0	118.0	117.1	117.0	116.9	117.0	117.0
1600.0	119.1	118.6	118.3	118.6	118.4	118.4
2000.0	121.6	120.3	120.9	120.9	120.9	120.9